HYDROLOGY OF GLACIERISED BASINS IN THE KARAKORAM

SNOW AND ICE HYDROLOGY PROJECT PAKISTAN

University of Manchester
Alpine Glacier Project

WATER AND POWER DEVELOPMENT AUTHORITY

Final Report
to
Overseas Development Administration

by

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January 1994

<u>Frontispiece</u> The context of snow and ice hydrology in the context of the Indian subcontinent: snow cover over the Himalayan ranges in April. This mosaic is from the U.S. Defense Meteorology Satellite Program, from CIRES archive at the University of Colorado, Boulder.

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1. Hydrology of the Karakoram and water resources in Pakistan

1.1 Introduction

The Indus basin has an area of 960 x 10^3 km^2 and the Indus itself, the backbone of Pakistan, is about 3180 km long. The annual average runoff of 220 km^3 (Shiklomanov 1993) gives an impression of plenty, but, as in Asia in general, more than 70 per cent of the annual flow occurs between May and October. Networks of canals distribute this water for the irrigation in the Punjab and elsewhere in Pakistan of 16 220 x 10^3 hectares of agricultural land , although the partition of India left the headwaters of the Indus itself and those of many of the left-bank tributaries thereof under the administration of India. The proportion of the total river flow arising outside Pakistan may be as high as 30 %, although quantification is difficult. Water resource per capita in Pakistan is 2.43 x10^3 m^3 (by comparison with 2.11 in the United Kingdom) but this statistic hides the strong seasonal variation experienced (Gleick 1993). One hundred thousand tonnes of sediment are estimated to be discharged to the Arabian Sea in the waters of the Indus each year (Milliman and Meade 1983).

Pakistan has an installed capacity of 2897 MW of hydroelectric power generation, about 34% of the total installed electric power within the country. Because of the seasonality of flow of the Indus main stem and tributaries, three large dams have been constructed: Javi (on the Javi), Mangla on the Jhelum river and Tarbela on the Indus, with capacities of 494, 7 252 and 13 690 x 10^6m^3 respectively. The topology and layout of the Indus drainage basin are shown in Figure 1.

A large proportion of the water (and the sediment) in the Indus is derived from the area of the basin located over the Karakoram mountains, which receives enhanced levels of precipitation orographically in winter from snowfall and during summer from monsoon rains. With many peaks above 8000m, the ranges of the Karakoram at the western end of the Himalayan-Tibetan massif maintain stable seasonal snowpack in winter and at higher elevations are highly glacierised, surprisingly so for the latitude (35 - 37^o N). Estimates of present levels of perennial snow and ice cover vary considerably, but about 15 000 km^2 is located in the middle ranges of the Karakoram, i.e. up to about 8 per cent of the area in which most of the ice occurs, that of the upper Indus basin (UIB) above the gauge at Besham (Fig. 1). Snow is accumulated from the westerlies in winter, when river flows remain at low levels .

It is during spring, summer and fall that runoff from the Karakoram mountains provides water to the irrigated agriculture of the Indus

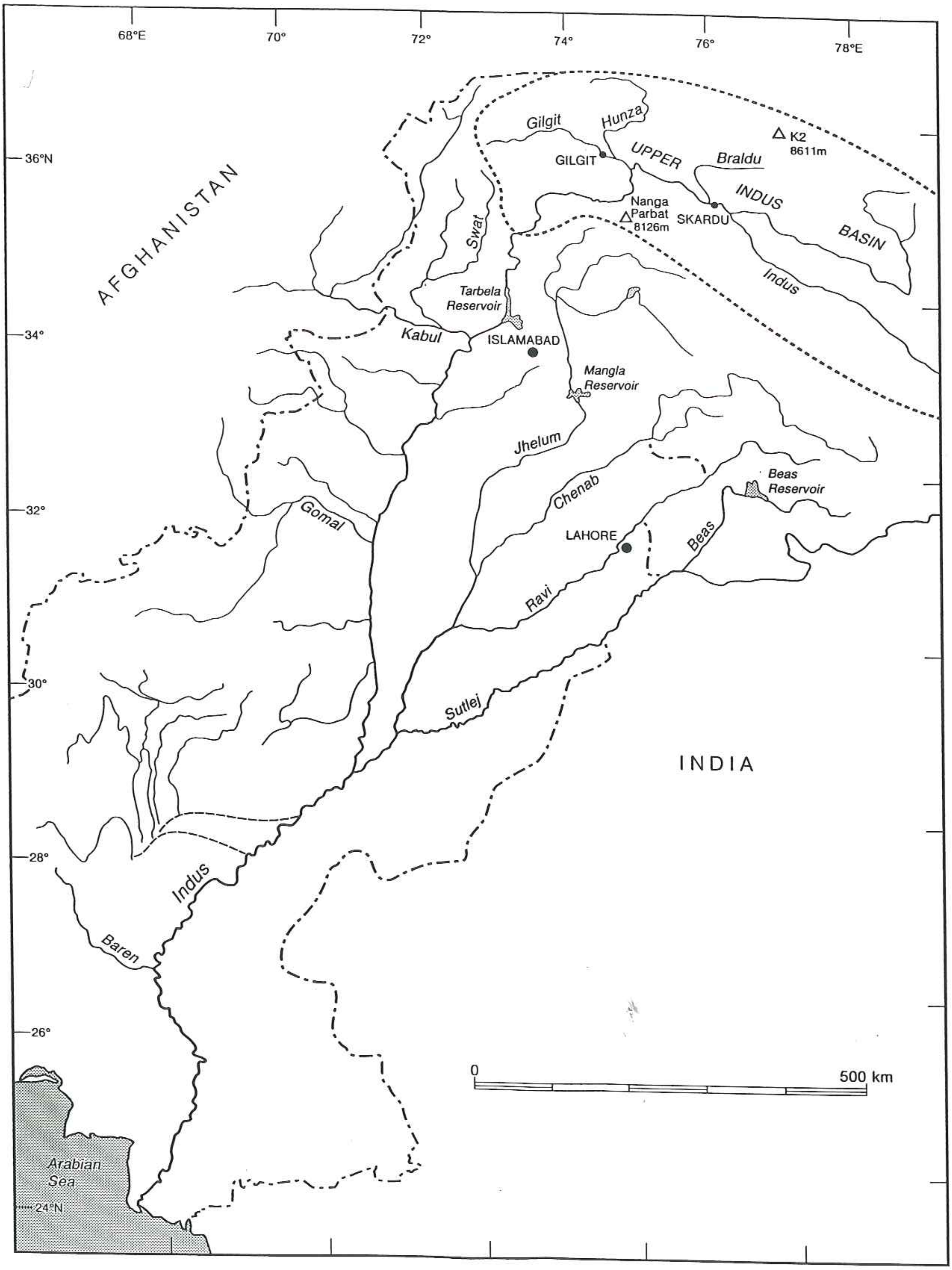


Figure 1. The drainage basin of the Indus in Pakistan and India. The watershed of the upper Indus basin (UIB) above Besham is delineated by a pecked line.

basin on which most of the population of Pakistan ultimately depends and to the major hydropower plants generating the electricity supply for the cities of the Punjab. Runoff from the upper Indus basin above Besham forms the greater part of the flow entering the Tarbela dam, largely snow- and ice-melt, augmented by contributions from monsoon rainfall on the southern slopes of the Karakoram.

Operation of Tarbela reservoir illustrates the interaction of hydrological processes in the mountains with the water resource systems of Pakistan. In general, by late winter or early spring, water stocks in the reservoir have been drawn down and inputs are low as precipitation remains stored as snow. Lack of water for power production leads to power cuts or 'load-sharing' in March through June, before flows in the Indus increase in spring with the onset of snow melt and later by the start of the monsoon rains. Snow- and ice-melt take on a critical role in those summers in which the arrival of the monsoon is delayed. During summer, the reservoir is soon refilled by snow-melt and abundant glacier-melt, but much of the latter is not retained running spectacularly over huge spillways to continue downstream. Construction of additional storage facilities on the Indus is needed in order to use this resource more effectively. On the down side, glacier meltwaters yield large quantities of suspended sediment, the ingress of which to reservoirs and Pelton wheels is of considerable detriment to water resource and power systems.

1.2 Hydrological processes in the Karakoram mountains

There are seasonal variations in discharge of the Indus and its principal tributaries, the Jhelum, Chenab, Ravi and Sutlej. These variations are marked and the regime of the Indus above Tarbela differs somewhat from the seasonal fluctuations in the other rivers which rise on the southern slopes of the Karakoram. The basins of the Jhelum, Chenab, Ravi and Sutlej have in general less perennial ice-cover, but receive abundant winter snowfall from the westerlies. Melting of this snow in spring leads to increasing flows, on the Jhelum starting the replenishment of the Mangla reservoir, which is completed during the ensuing monsoonal rains in summer. Summer precipitation occurs in large quantities extensively over the plains of the Punjab and is intensively heavy in the mountainous areas of these basins. The Jhelum, rising on the southern flanks of Nanga Parbat, additionally has an important headwater glacier component.

The main stem of the Indus drains the glacierised higher Karakoram mountains. Towards, and then south of, Besham, the Indus basin has a similar precipitation regime to the southern slopes of the Karakoram, although levels of precipitation in summer decline to the west. Further north, the seasonal regime of runoff of the partially-glacierised UIB is dominated by sustained melting of glacier ice during the period June through September. There is a snowmelt influence earlier in the year in the spring months of March through June, according to elevation. Monsoonal precipitation in summer is of much less significance in the UIB than over the southern slopes, except for particular periods in certain years.

The quantity and timing of discharge in Karakoram rivers with snow- and ice-melt components of runoff depend therefore on amount, incidence and form (liquid or solid) of precipitation, and on thermal regime which determines the patterns of melting in spring of the amount of winter snow pack available and of the melting of perennial ice throughout summer in those basins which are glacierised. The timing and intensity of monsoonal rain storm inputs also determine the shape of the hydrograph, and lead to extensive flooding particularly in the basins of the four left-bank tributaries of the Indus.

1.3 Attempts at forecasting flows in the Indus and its tributaries

Several models for operational forecasting of floods emanating from the mountains in the lowland rivers and for optimising the use of the capacity of the reservoirs have been devised. For forecasting floods in the Jhelum, a model was proposed by WMO (Moser and Naef 1984), in which six telemetered rain gauges in the lower part of the basin were used. Localisation of intense precipitation made forecasting difficult. WMO noted that for the upper part of the basin, account would need to be taken of snow-melt runoff. Lack of real-time data (especially from the Indian headwaters) and of mountain temperature data are severe constraints for such forecasting.

A different approach has had to be taken for the prediction of flow in the UIB above Tarbela. This has involved the use of statistical relationships between the area of the basin covered with snow in spring and the runoff volume during the snowmelt period (e.g. Makhdoom and Solomon 1986). The larger the area of snow cover, the more snow on the ground at the end of winter and hence the greater the quantity of runoff that will be produced. Such methods are useful in remote mountain regions since field measurements are difficult and expensive, and remote sensing can look over international boundaries. In basins subject only to seasonal snow cover, results are not unreasonable, but in glacierised basins, extensive snow cover may actually reduce runoff. A thick snowpack will, through high albedo, retard the rise of the transient snowline.

Underlying ice, with lower albedo, and meltwater production higher than for snow, given an equal amount of radiation received, is protected from melting until later in the year (Ferguson 1985, Collins 1989). Summer precipitation events which produce storm runoff in the lowland areas greatly reduce runoff from glaciers should such fall as snow at high elevations.

The underlying physical relationships between climatic variables and discharge from glaciers are reasonably well-known, usually from investigations in small highly-glacierised basins in alpine mountains.

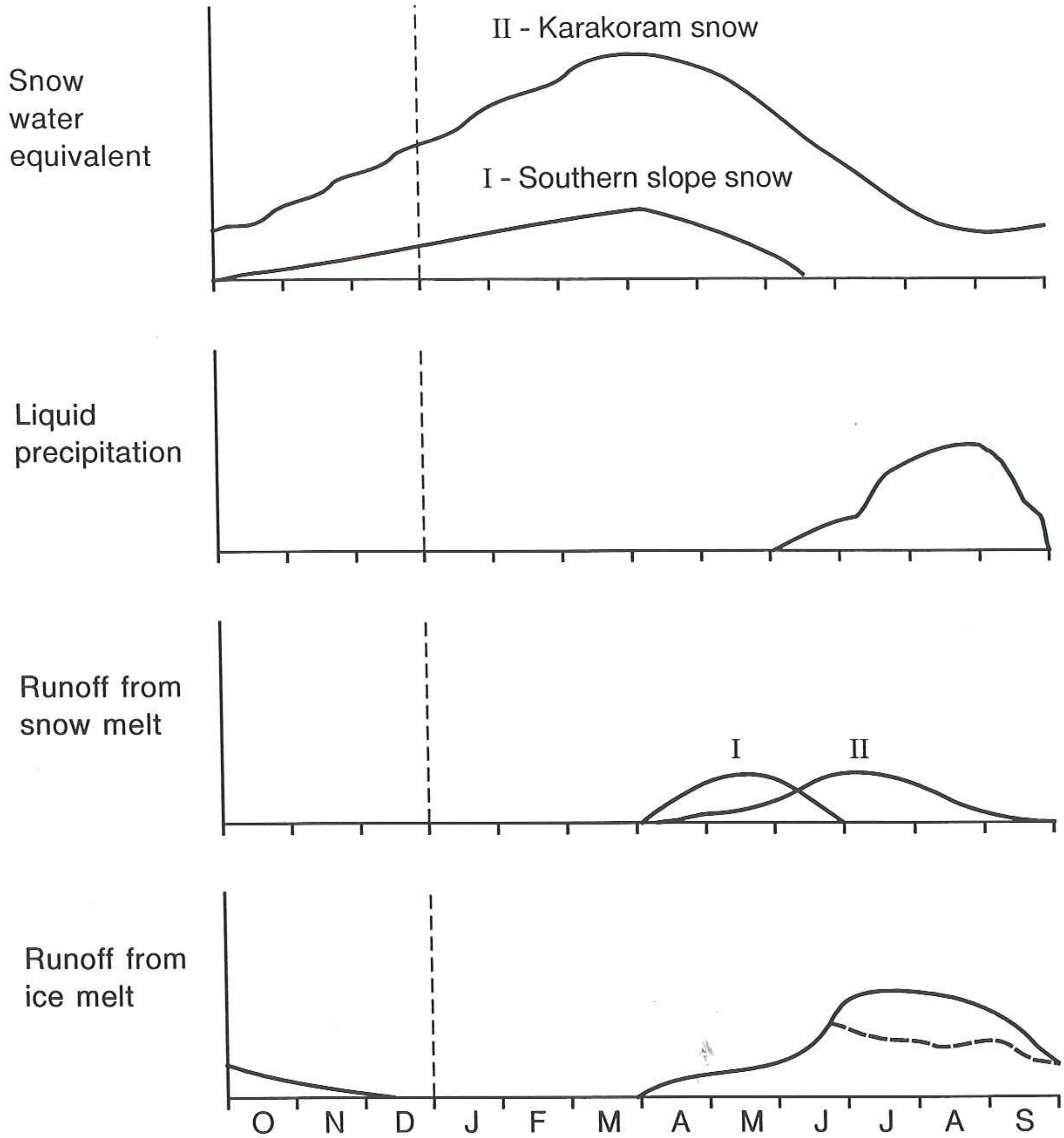
In order to develop models of runoff in which incorporate snow and ice components arising in the glacierised basins of the UIB, measurements of climatic variables, such as incoming global radiation, air temperature, lapse rate and precipitation are necessary continuously through time together with measurements of glaciological characteristics such as mass balance, ablation of ice and accumulation of snow. Determinations of stage-discharge relationships in rivers at stations close to glacier snouts are also required, with continuous monitoring of stage. From the viewpoint of reservoir management or future dam construction, estimates of suspended sediment transport in meltwaters are needed.

Essentially, in the upper Indus basin, a design for a hydrometric network was needed, which would meet the twin requirements of characterising hydrometeorological inputs over a wide area and quantifying the resultant responses in runoff initially from specific glaciers, but with the ultimate intention of widespread generalisation.

2. Conceptual model of the hydrological regime of Karakoram rivers

2.1 Seasonal variations of the components of runoff

Seasonal fluctuations in components of the basin hydrological cycle under various conditions in Karakoram mountain catchment areas are shown schematically in Fig. 2. Water equivalent held in the winter snow pack will be greater and remain longer in spring at higher elevations which zone corresponds also to the areas maintaining glacierisation. Both the quantities of water stored and the elevations at which the storage occurs affect the pattern of melt and the timing and volume of release of meltwater from snow. Precipitation during the monsoon season decreases with distance to the north and west, but this gradient is offset to an extent by precipitation being enhanced at higher elevations. The duration of



<u>Figure 2.</u> Schematic representation of the seasonal variation of water equivalent held in snow on the southern flank (I) and on higher summits (II) of the Karakoram (top); liquid precipitation in the southern areas subject to monsoonal incursion (including I) (centre upper); snow melt runoff at lower elevations (I) and at high altitude (II) (centre lower); and the pattern of runoff from fusion of glacier ice (bottom) under clear skies and relatively (pecked) in areas with monsoon cloud cover.

rainfall contributions to runoff similarly will decline to north and west, with a baseline range of early July to late September in the Punjab basins.

The pattern of runoff derived from ablation of ice depends on the rate of removal of the winter snow cover (a function of thermal conditions and the quantity of winter snow - both of which have an altitudinal component). Essentially the rise of the runoff hydrograph in spring is controlled by the rate at which the transient snowline rises, before decline takes over accompanying the reduction in radiation after the solstice and the associated but lagged fall in air temperature. Cloud cover interacts with the availability of heat energy, such that in areas subject to the monsoon ice-melt will be reduced.

The overall runoff from a basin is made up of the sum of the values of each of the individual components at each point in time. Actually, the runoff curve for a river reflects the specific effect of each process (i.e. per m^2) multiplied by the proportion of the basin area involved. This might be, for example, a declining snow-covered area, decreasing in size but with enhancing melt-rate, as the area of exposed ice and ice-melt rate increase in early summer. The proportion of a basin area involved is important in determining quantitatively-differing responses to the same thermal and precipitation inputs in catchments of differing percentage glacierisation.

2.2 Altitudinal variations

In addition to understanding the relative contributions of rainfall, snow-melt and ice ablation, vertical organisation of thermal and precipitation processes have to be taken into account. Precipitation and global radiation increase with elevation just as air temperature decreases. Annual total precipitation in valleys of the Karakoram is between 80 and 160mm, whereas at least 2 - 3 m of water equivalent must fall at high elevations. Slope and aspect also influence radiation. At the equilibrium line, the quantity of snow is such that the available heat energy is just unable to melt all the precipitation.

3. The upper Indus basin

3.1 The basic hydrometric network

The upper Indus basin contains most of the snow and ice resources of the Karakoram and provides the most suitable area for detailed investigation of the formation of the glacial component of runoff.

A network of gauging stations has been operated by WAPDA in the UIB since the 1960s. The gauge on the Indus at Attock, with over 100 years of records, is located to the south of the Tarbela reservoir and so since 1967 Besham has usually been taken as the station defining the Karakoram portion of the overall basin, and effectively now fixes the extent of the UIB (163 x 10^6 m^3) as shown in Fig. 1. The highest specific discharges in the Karakoram are from the south-west flanks of Nanga Parbat, where monsoon rain and glacier melting interact. The 8 gauges on the Indus, and (usually) on principal tributaries immediately before their confluences with the main stem in the UIB, point to the glacierised Astor basin gauged at Doyian as the highest and the Hunza basin as the second highest specific water yields (0.94m and 0.90m $year^{-1}$ average between 1967 and 1975 respectively), the Hunza contributing more than 16 per cent of the total flow of the UIB from 8 per cent of the area.

With the exception of Doyian (to which drains melt from the north side of Nanga Parbat), the gauges are located at bridges on the Karakoram Highway or at bridges on principal ancillary roads. The nature of the terrain, with rivers deeply incised in gorges in turn often in deeply-trenched valleys, makes the Indus valley the only major routeway. The Hunza basin is the most accessible basin along the continuation of the Karakoram Highway to the Khunjerab Pass. At 28.46% glacierisation, the Hunza at Dainyor (Dainyore, Danyore, Danyor) Bridge has the greatest glacierised area in a gauged basin, and is effectively the highest point upstream at which the glacier runoff signal is measured. The stage boards are usually read hourly between 08.00 and 16.00.

3.2 Meteorological stations in the Hunza basin

The Hunza is gauged at Dainyor Bridge a few kilometers upstream of the confluence with the Gilgit River, which is about 10 km east of Gilgit airport. Meteorological measurements have been maintained at Gilgit airport (1490m a. m. s. l.) since the 1960s, and mercury-in-glass thermometers in Stevenson screens read twice or three times a day. The Meteorological Department (in Lahore) also maintains precipitation measurements at Gilgit.

Air temperature and precipitation measurements are collected manually also at Karimabad (2405m), and were collected formerly at Mishgar (3088m), which was the highest meteorological station in the Karakoram. Summary data are presented by Whiteman (1985), and indicate variable temperature lapse rates according to pairs of stations used and month of measurement. In August for example, Gilgit and Mishgar indicate lapse rates of -5.0 ^{o}C km^{-1}, but in

September -3.1 ^{o}C.

Daily total precipitation measurements at these stations show no increase with elevation, emphasising that the valley bottom locations of the stations suffer the impact of topographically-induced microclimate.

3.3 Glaciologically-relevant hydrometric issues

The Water and Power Development Authority of Pakistan (WAPDA) recognized that in attempting to overcome the pressing water management problems in Pakistan, questions relating to snow and ice contributions to runoff would have to be answered.

Immediately, it becomes apparent that the basic hydrometric network is not appropriate to the measurement of thermal and hydrological fluxes in Karakoram mountain basins, and that a system of measurement stations would have to be developed for the measurement of climatic characteristics in glacierised basins, over the range of elevations in which fusion of snow and ice occurs, and for determining the flow of rivers close to glacier termini.

Ideally, a period of measurement in which observations would be undertaken in a variety of basins should precede selection of a flagship basin, which if not strictly representative of glacier drainage basins, would at least show the general pattern of behaviour through time experienced throughout the region, and on which effort might be subsequently concentrated.

4. Scientific and practical questions

Several interesting scientific questions arise in addition to specific basic questions concerning the quantities of runoff generated by melting of snow and ice.

The principal issues are:

1. What are the seasonal variations in the amounts of runoff derived from melting of snow and ice in the tributaries of the Indus?

2. How much do the timing and magnitudes of seasonal variations of runoff change from year to year, and in response to what synoptic climatic conditions?

3. Which hydrometeorological variables at which measurement stations are best related to runoff variations and might ultimately be used to predict variations in meltwater flows into the Indus?

4. What delay arises within glacierised basins between melt

production and discharge at the glacier terminus?

5. What is the role of storage of snow and ice in the water balance of basins of differing percentage glacierisation in the Karakoram?

6. How much suspended sediment is transported in meltwaters draining from glacierised basins?

The terrain of the UIB above Besham is a large area of 162.4×10^3 km^2, which clearly lies at the margin of influence of continental and maritime climatic influences. Rugged terrain including peaks routinely in excess of over 6000m a. s. l., deep valleys, and variations of climate with elevation such that precipitation amount can easily increase by 2 orders of magnitude in a basin, and that heavy snow can fall at high altitude during light drizzle 3000m below may preclude any general regional response. Since settlements and hence established meteorological stations are located in valleys at base elevations evidently occupying topoclimates between intervening massifs, some high level, yet accessible, sites for meteorological instrumentation are needed. As in other Asian mountain areas, communication lines are few, following wide, deep, turbulent and swift flowing rivers, which are crossed by few rigid bridge structures from which gauging the large rivers would be most practicable.

The sites at which runoff is ultimately to be forecast (Besham or Mangla) are outside the mountain environment proper, and downstream routing is of great importance, although not part of this study of the glacierised headwater tributaries. Questions of representativeness of observations are more serious in mountain terrain than elsewhere. If, as Klemes (1990) claims, modelling of high mountain hydrology is the 'ultimate challenge' in hydrological sciences then obtaining suitable data to drive and calibrate those models must be the penultimate.

Although all hydrological phenomena are characterized by variation from year to year and are subject to extremes and high magnitude events, the role of snow and ice in hydrology introduces also the longer-term variations which arise as a result of changes in the amount of water held in storage in glaciers and the response of such storages to fluctuations in climate. At present, worldwide, there appears to be destocking of water from glacier storage; that is, more runoff is being generated than precipitation puts back. Glacier size is declining. This cannot go on for ever as the resource will become depleted and will approach equilibrium causing river flows to decline after the initial period of increase.

In the case of Pakistan, the potential for declining meltwater resources with global warming during the next forty years, during which population growth shows little sign of abatement, may have serious consequences.

5. Involvement of Alpine Glacier Project (UMAGP) in Snow and Ice Hydrology Project, Pakistan (SIHP)

5.1 Background to SIHP

The Snow and Ice Hydrology Project (SIHP) was conceived in 1981 as a collaborative programme of study of snow and glacier hydrology in the upper Indus basin and Karakoram mountains. Investigation of the water balance of the upper Indus had been recognized as important in the 1970s, and limited measurement of seasonal snow-covered area using Landsat imagery was attempted, coupled with a simple snowmelt forecast. The SIHP was initially to run from 1984 to 1987 as a cooperative venture between the International Development Research Centre, Ottawa and the Government of Pakistan. Wilfrid Laurier University was the partner organisation with WAPDA, and fieldwork was undertaken in the ablation seasons of 1985 through 1988. Personnel from other Canadian universities were also involved. A description of the programme and its aims is given by Hewitt and Young (1993)

5.2 UMAGP fieldwork

Members of UMAGP were invited to participate in 1986 and between May and August of that year undertook field hydrological measurements. The original purpose was to assist WAPDA with gauging glacier-fed rivers. ODA supported this participation from 1988, but the equipment procured by the Crown Agents was not available until the 1989 season. ODA then supported fieldwork in 1989 and 1990, the funding terminating 2.5 months after the end of the field season. Two further seasons followed in 1991 and 1992. Canadian involvement in fieldwork declined after 1988. After a long and fruitful season in 1989, WAPDA management appeared to change. WAPDA involvement in the field in 1990 was much reduced and afterwards whilst interest was maintained, field participation was not forthcoming.

5.3 Aims of SIHP

The main aims of SIHP were:

1. to initiate research into glacio-hydrological aspects of the UIB relevant to water resource development and forecasting.

2. to define the terms of an on-going monitoring and forecasting system for snow and ice regime basins.

3. involve and train WAPDA personnel in glacier hydrology.

The original hydrometric aims of SIHP were:

(a) to provide a database of hydrological, glaciological and hydrometeorological information to enable improved forecasting of seasonal runoff.

(b) to put in place a measurement network

(c) to identify useful variables for whatever forecasting model was chosen

(d) to measure sediment loads of glacier-fed rivers

5.4 UMAGP responsibilities

Within the broader SIHP remit, UMAGP has taken responsibility for measurement of riverflow (with WAPDA) and for measurements of sediment and solute transport in meltwaters.

Riverflow and water quality data were to be collected at several sites, the locations of which were to be selected with reference to the variability of seasonal components of runoff within the UIB, locations of pre-existing WAPDA gauges, and sites selected by Canadian SIHP members for glaciological and climatological measurements.

6. Hydrological measurement programme

6.1 Initial selection of glacierised basins for SIHP

Given the initial objectives, and taking into consideration the desirability of a wide regional base with observations undertaken in a variety of basins in the UIB (see 3.3 above) for a period before selection of one (or more) flagship basins, several rivers draining glacierised basins of various percentage ice-cover were selected for measurement.

The selection of the Biafo-Hispar glacier system as a potential high altitude meteorological site by the Canadian group determined the initial gauging stations. From high elevation accumulation basins, Hispar Glacier descends westwards and its meltwater enters the Hunza (Figure 3). Meltwaters from Biafo Glacier drain south-east to the Braldu, which becomes the Shigar, a right bank confluent joining the Indus at Skardu (inset to Fig. 3). Climatic data were recorded between July and August 1985 and June and September 1986 at 4080m (Wake 1989).

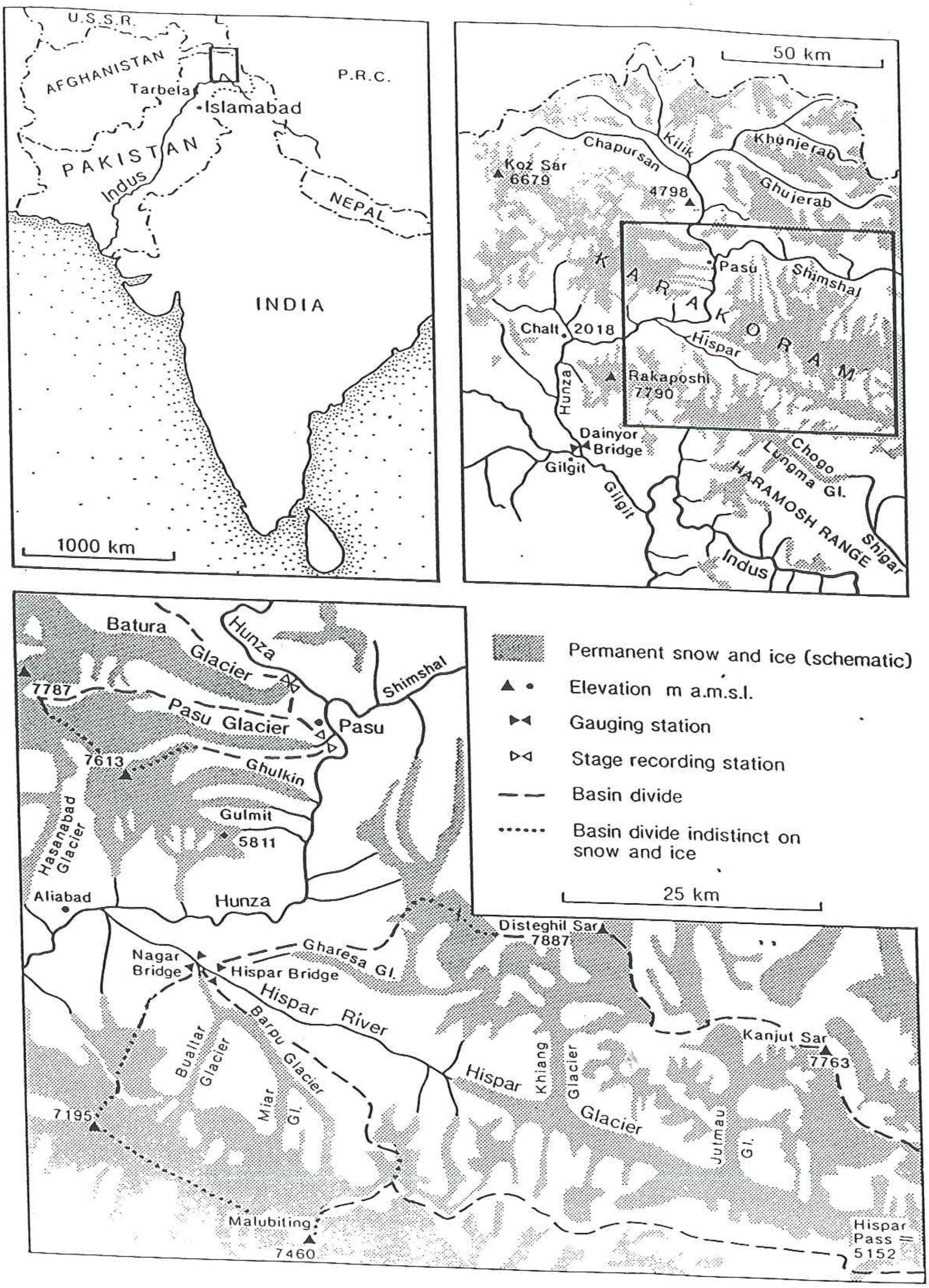


Figure 3. The drainage basin of the Indus in Pakistan (left upper), the upper Indus basin in the Karakoram (right upper), and the flagship gauging stations on Passu and Batura rivers.

Gauging stations however have to be selected according to logistical demands. In order to gauge large meltwater rivers using current meters by the suspension technique, a sufficiently stable bridge is required from which the current metering equipment together with a substantial steadying counterweight (up to 100 kg) can be lowered, at various positions across a transverse section, into the fast flowing water.

In the deep valleys of the Karakoram, therefore, sites suitable for gauging rivers draining glacierised areas are dictated by the availability of substantial bridges, the spans of which can bear vehicular traffic, whether current meter trolley or support jeep. Glacier basins suitable for consideration as hydrological research basins are therefore initially defined by where a valley bottom road bridges a proglacial outflow stream.

This precondition was met at Dassu on the Braldu, which defines a basin also including Baltoro Glacier. A stage board site at Askole, selected by WAPDA, above the confluence of the Biafo River with the Braldu was one-day distant from the roadhead, and unsuitable for gauging.

Suspension bridges across the Hispar at Nagar Bridge and upstream where the road to Hispar also crosses to the left bank provided suitable gauging sites.

6.2 WAPDA gauging in 1985 and 1986

At the onset of the SIHP, WAPDA installed five stage boards in November 1985 at the locations listed in Table 1, which include also Tatta Nala, a stream flowing from Nanga Parbat directly into the Indus at Rakhiot, bridged by the Karakoram Highway. Stage readers were appointed and as is usual at WAPDA gauges, measurements were made in daylight on the hour between 08.00 and 16.00 local time every day. The boards in the Braldu basin were destroyed on 1 August 1986 and not replaced. Stage observations, supported by occasional gaugings, were continued on the Hispar until May 1988 when the stage readers were dismissed by WAPDA.

Bucket-type current meters with hand-raised and lowered counterweights mounted on unstable U.S. Geological Survey trolleys dating from the 1930s failed to dampen the enthusiasm of field personnel, (Plate 1), but the close spacing of suspension cables on bridges made progress slow and exhausting.

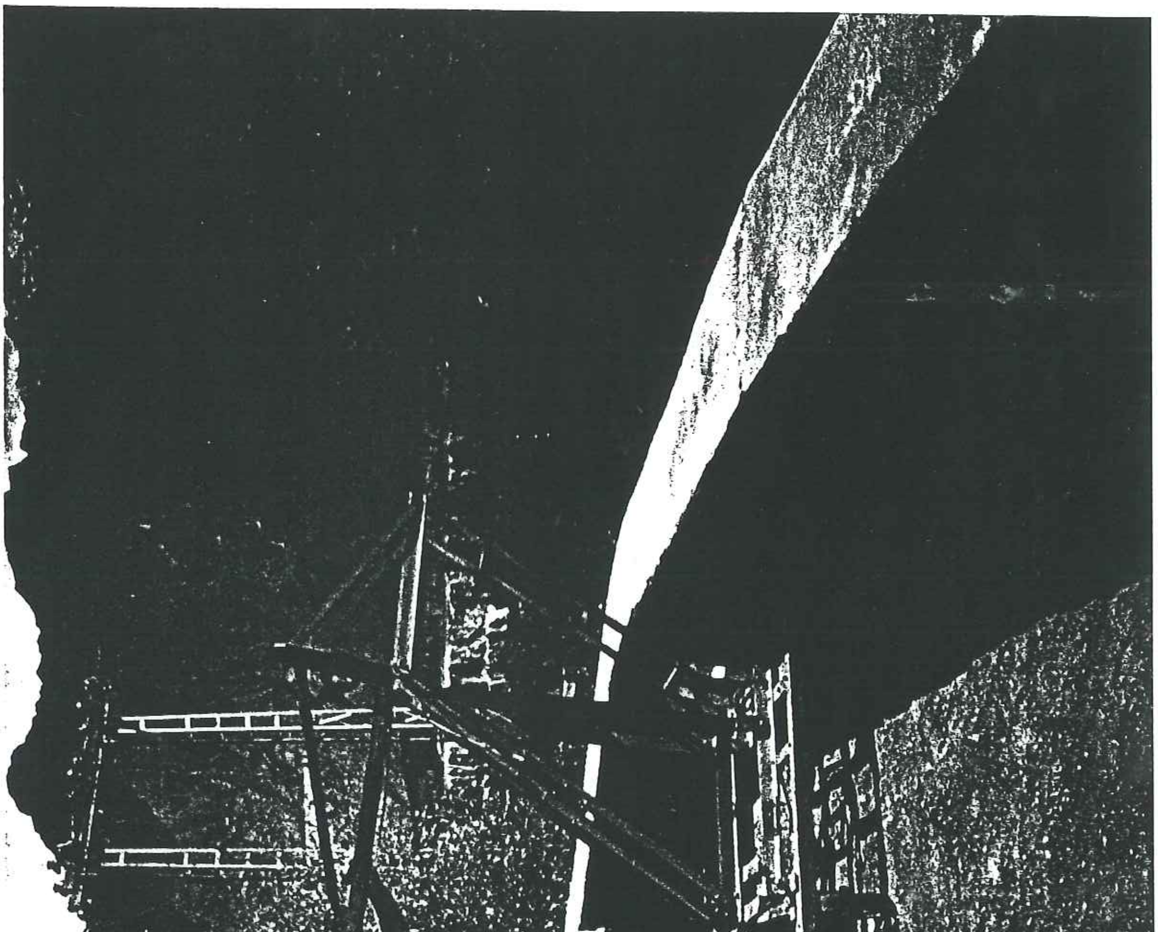


Plate 1 A cumbersome trolley from which current metering equipment is lowered manually into the Hunza River at Dainyor Bridge gauging station.

6.3 WAPDA gauging in 1987 and 1988

As principal valleys in the Karakoram are so arid, there are few if any other tributaries to the major rivers than those which arise from glaciers. Where a principal river is bridged upstream and downstream of a glacier-fed tributary, flow from the glacier can be obtained from the difference between discharge measured at the downstream and upstream bridges. This method was used by Lanzhow Institute of Glaciology and Geocryology (1980) to estimate the flow from Batura Glacier by gauging the Hunza above and below the confluence with the Batura River, the bridge over the latter having been destroyed by an outwash flood. (One of those bridges over the Hunza now no longer has a vehicle deck).

The river draining meltwater arising from both Barpu and Bualtar glaciers, the outflow of the former passing under the tongue of the latter in its lower 500m, is gauged by subtraction of the flow of the Hispar River at Hisper Bridge from that at Nagar Bridge. The combined Barpu and Bualtar glacier system was intensively investigated by Canadian participants in SIHP in 1986 and 1987. The gauge at Hisper Bridge defines also the basin containing Hisper (variously Hispar) Glacier (Figure 1).

6.4 UMAGP gauging in 1989 through 1992

Measurements at Hisper Bridge and at Nagar Bridge would have continued had a slide of scree not blocked the road to Hisper. Also, the stage-discharge rating curve at Hisper was poor.

In 1989, stage was recorded at six stations in the Hunza basin; for short periods on the Hunza itself upstream of Batura at Galapin, on the Minapin and Hassanabad tributaries close to the respective glacier snouts before confluence with the Hunza downstream of Aliabad, at the WAPDA long term gauge at Dainyor Bridge at the mouth of the Hunza basin, and on Passu and Batura rivers, within 1 km of the respective glacier snouts, utilising bridges where the Karakoram Highway crosses the rivers between the respective snout and confluence of the proglacial river with the Hunza, some half kilometer downstream of the bridges (Figs 1 and 3).

Additionally in 1989, three stations were set up for short periods in the Shigar basin, at Shigar, upstream on the Braldu at Dassu, and on the tributary emanating from Chogo Lungma glacier (Figure 1).

At WAPDAs suggestion, these distant widely distributed stations operated only briefly, and not subsequently. Theft of equipment, Shia villagers hostile to Sunni WAPDA personnel, and long travel times between stations (at least 12h one way from Hunza to Shigar on days when roads were free of slides and stranded trucks), together with fairly successful gauging at Passu and Batura helped decisions move in favour of the latter two as 'flagship' stations.

The full program of SIHP river discharge measurements between 1986 and 1992 indicating UMAGP achievements is listed in Table 1.

6.5 Long term gauging stations operated by WAPDA

The gauging stations operated by WAPDA on the principal rivers tributary to the Indus and on the Indus itself in the UIB above Besham continue in service. Unfortunately, the data for the period of measurements in 1989 and later have not been made available, nor have the gauging data at the time of parallel measurement at Dainyor Bridge.

7. Objectives of UMAGP

Within the above framework and constraints, the aims for each of the stations selected were:

1. to obtain a continuous high quality record of stage throughout the seasonal cycle of flow.

2. to obtain a reliable stable stage-discharge relationship with measurements of discharge being undertaken throughout the range of stage experienced.

3. to record electrical conductivity of meltwater continuously as a surrogate measure of total dissolved solids content.

4. to collect hourly instantaneous samples of suspended sediment transported in meltwaters with a view to assessing sediment delivery from large Karakoram glaciers.

5. to collect appropriate hydrometeorological data at high elevation.

8. Methods developed

8.1 Stage recording

Several vertical stage boards against which water levels can be read have to be used in natural sections of large rivers with widely fluctuating seasonal discharge. In Pakistan, WAPDA uses the arrangement of boards shown in Figure 4 and Plate 2. Stage boards of up to 5m vertical length are displaced up the banks at intervals such that before the rising water surface has submerged one board, its level can already be observed against the next board upslope. In turbulent rivers, with standing waves, oscillations of the water

Table 1. Hydrological data collected during SIHP by UMAGP and WAPDA

Basin	River	Gauge	1986	1987	1988	1989	1990	1991	1992
Main-stem gauging stations (WAPDA)									
Gilgit	Gilgit	Gilgit	o	o	o	o	o	o	o
Gilgit	Gilgit	Alam Bri	o	o	o	o	o	o	o
Gilgit	Hunza	Dainyor	o	o	o	o	o	o	o
Indus	Indus	Besham	o	o	o	o	o	o	o
Stage boards (WAPDA)									
Shigar	Braldu	Askole	x						
Shigar	Braldu	Dassu	x						
Hunza	Hisper	Hisper Bri	x	x	x				
Hunza	Hisper	Nagar Bri	x	x	x				
Indus	Tatta Nala	Rakhiot	x						
UMAGP gauging stations									
Hunza	Passu	Passu				x	x	x	
Hunza	Batura	Batura			x	x	x	x	x
Hunza	Hisper	Hisper Bri		x		x			
Hunza	Hisper	Nagar Bri		x		x			
Hunza	Minapin	Minapin				x			
Hunza	Hunza	Galapin				x			
Hunza	Hasanaba	Hasanabad				x			
Hunza	Hunza	Dainyor				x			
Shigar	Braldu	Dassu				x			
Shigar	Shigar	Shigar				x			
Shigar	Chogo Lungma					x			
ODA funding						x	x		
ODA Equipment available for use						x	x	x	x

o - collected by not available to UMAGP
x - collected and available to UMAGP

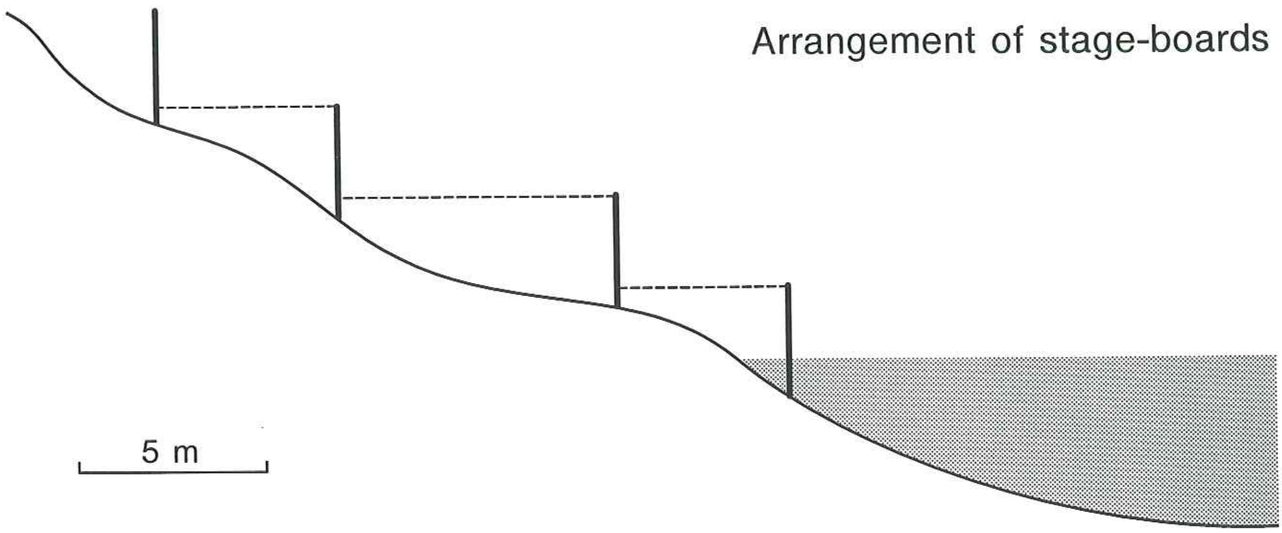


Figure 4. The arrangements of stage boards on the banks of a large river subject to large annual ranges of discharge.

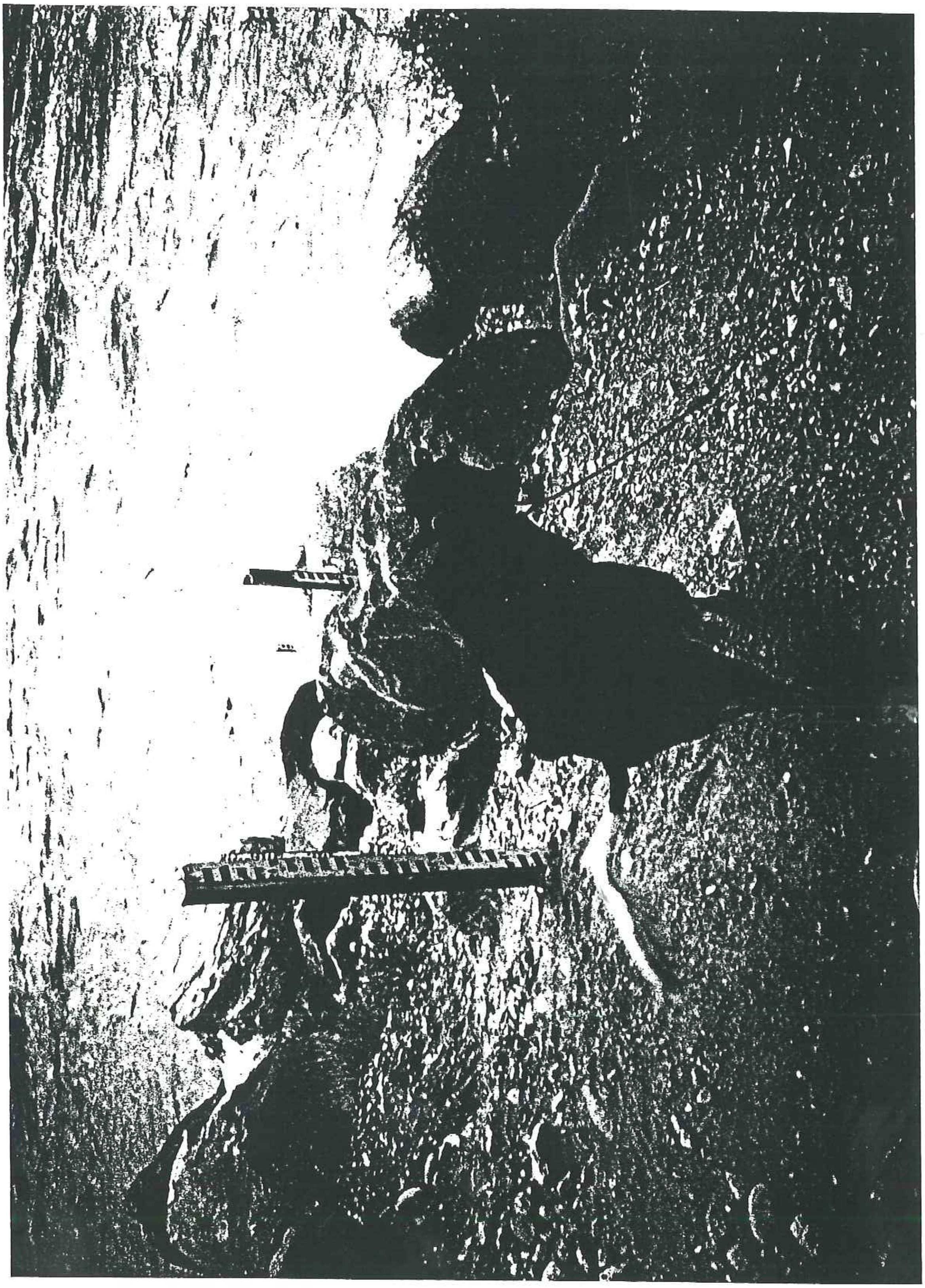


Plate 2 WAPDA stage boards at the Dainyor Bridge gauging station on the Hunza River.

surface necessitate some estimation, but accuracy within a centimeter can be expected from an experienced reader.

Stage boards are free standing, cemented into boulders or mounted on vertical angled-steel bars which are driven into bed/bank sediment. Turbulence, standing waves and bedload transport in glacier-fed rivers, particularly at high discharges during the summer ablation seasons, tend to lead to destruction of boards, particularly those in lower portions of the channel. Stage boards at Passu, Nagar, Dassu and Galapin were removed by high flows during the periods of observation at those stations.

The usual automatic method of monitoring stage in a manner useful for continuous recording in turbulent mountain streams is to utilise a counterbalanced float in a stilling well. This is installed in a relatively stable cross-section of river, delimited by bedrock, or artificially stabilised where possible by the filling of gabions, a technique widely used for example in the Rocky Mountains in Canada. A corrugated steel tube or culvert pipe is held vertically, attached to rock, a large boulder which the highest flow is not competent to move or a gabion. If there is sediment on the bed, the pipe is driven in to some depth. Such a stilling well is usually located at or close to the channel margin in order to promote permanency. In rivers with seasonal ranges of stage of several metres, stilling wells have a tendency to be left high and dry in the low flow season (as in winter in the Karakoram).

Float level recorders or loggers attached to potentiometers turned by the rising and falling of the float are used to produce graphical or digital data respectively. An initial experience in 1986 at Hisper produced a minimal change in level with increased flow, as scour of the bed occurred at high flows in the main deep section of the channel, and the thread of faster flowing water moved towards the opposite bank.

Pressure transmitters, attached to Technolog solid state loggers, were installed at the UMAGP gauges, and, for the purpose of evaluating the stage reading technique, also at the WAPDA gauge at Dainyor Bridge, with a view to obtaining continuous stage records. TransInstruments transmitters were used. Transmitters have an advantage over pressure transducers in that each transmitter has a linear current output (4-20mA) variation with changes in water pressure (i.e. depth). Therefore calibration of particular transmitters with each individual data logger is not required. Transmitters are maintained at atmospheric pressure internally through pressure equalization made possible by a 1mm diameter breathing tube intersheathed with the wires in the cable from the sensor to the logger, the air pipe being open to the atmosphere at the point where the cable enters the logger casing. The transmitters were attached to Dexion angle-iron supports of lengths up to 3m and attached to boulders, bridge supports or gabions. Positions were marked carefully to ensure that the sensor was acting as a fixed bench mark and reference to which measurements of water level could be related throughout the SIHP. Stage boards were retained where possible in order to allow performance of the transmitters to be checked against actual observations.

Transmitters were initially installed unsheathed, but failure of several occurred within a few months. Silt-sized sediment particles entered the immersed transmitters and damaged the strain gauge mechanism. Experience in UMAGP in projects in Switzerland around the same time suggests that TransInstruments transmitters are no more prone to this problem in meltwaters than other are transmitters (or transducers) from other manufacturers. Subsequently, transmitters were encased in thick gauge polyethylene bags, which were filled with engine oil and sealed to the transmitter with adhesive tape. Re-sheathing was frequently necessary as even thick gauge polyethylene was abraded and then quickly shredded by sediment but the failure rate was greatly reduced. The transmitter output signal is damped by the logger and time averaged during data reduction, this being equivalent to the use of a stilling well. Values were recorded every 10 minutes throughout the measurement period, and then reduced to hourly mean values. Some dramatic short-lived (one 10-minute measurement) fluctuations of transmitter output were recorded, which were so great that they suggest that stage would have been halved and then recovered to the original value in 10 minutes. Sudden events of that magnitude were not observed and an equipment instability is thought to have been responsible. Where such noise was found in the record, the value was removed and replaced with the default value for missing data.

Technolog Tinylog dataloggers were coupled with the transmitters, proving reliable under normal conditions of operation. All stage information was logged at 10 minute intervals, on the hour, at ten minutes past and so on. Failures occurred if rainwater entered the weatherproof storage boxes on site (usually after tampering) and in winter when the internal Li batteries tended to fail at temperatures considerably lower than zero. In September 1989, all the stage data for August at Batura was lost when the external sealed rechargeable Yuasa 12v battery was removed before downloading the data to the disk of the laptop PC. This resulted from an unexplained random failure of the internal Li battery. Subsequently, data were downloaded every few days, and chart recorders used also to shadow the loggers.

Thankfully, this accident was not re-enacted subsequently.

8.2 Measurement of velocity

WAPDA ordinarily uses vertical shaft cup-type current meters for gauging large rivers by the suspension technique. 1930s American-designed crane-trolleys form the basis of the suspension apparatus. From the trolley, the current meter and 92kg (200 lb) weight are raised and lowered manually, often though 20m or more, many times during a gauge particularly on suspension bridges. The jointed nature of the decking of suspension bridges also makes operation difficult.

This system was to be replaced by propellor-type current meters, suspended from a bracket mounted on the roof of a Landrover, with a power-driven winch to raise and lower the current meter and weight into the water. The scheme designed is shown in Figure 5 and Plate 3. The derrick, from which the current meter is suspended, swivels through 90^0 from the position shown to travel aligned with the length of the vehicle.

The equipment was constructed by Braystoke to the design of UMAGP, with some practical modifications. Mechanical transmission from an electric motor through cog wheels to the former around which the suspension cable is wound was the Achilles heel of the design. The drive soon failed with the fracture of cog teeth, and the manual stand-by brace became the accepted method of operation. Actually, this was no hardship. A future build would not use a mechanical power drive. The construction was limited to suspension of a 50kg weight, the maximum that the roofrack, crane and suspension cable could support. 50kg was inadequate and the current meters and weights were tossed around with considerable displacement of the suspension wire in a catenary downsteam in the more turbulent rivers in high flows at the height of the ablation season in July and August everywhere, and at almost all times at Batura.

The Braystoke current meters themselves were not sufficiently robust for the conditions met in swift-flowing turbulent meltwater rivers. The soft polyethylene moulded tail fins (see Fig 5 inset), essential for lining up the body of the current meter with the direction of maximum flow velocity could be dragged from their mountings in the body of the instrument and the axle and bearings supporting the propeller twisted and damaged by the flow. Nevertheless, frequent gauging was possible and reliable and replicable stage-discharge relationships were obtained at several stations.

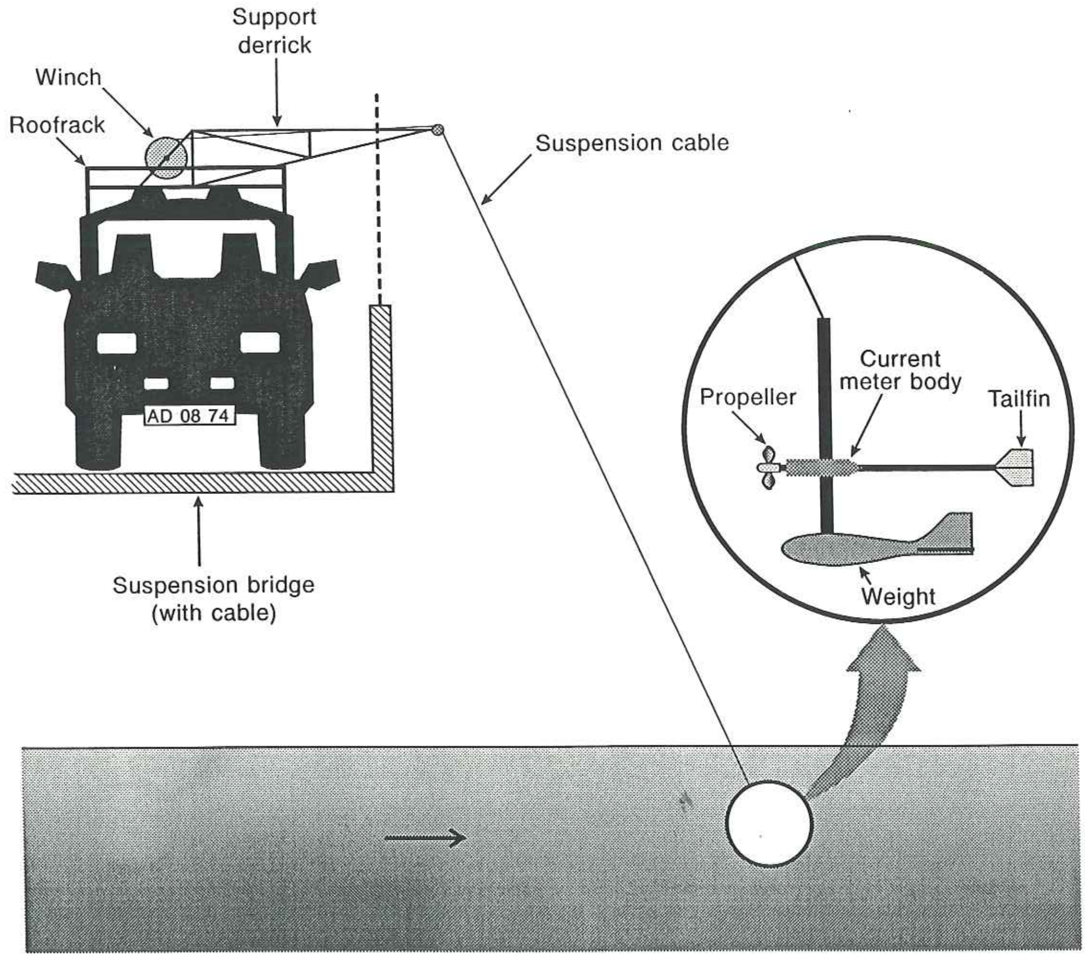


Figure 5. Schematic representation of the roofrack mounted current metering equipment used in the project.

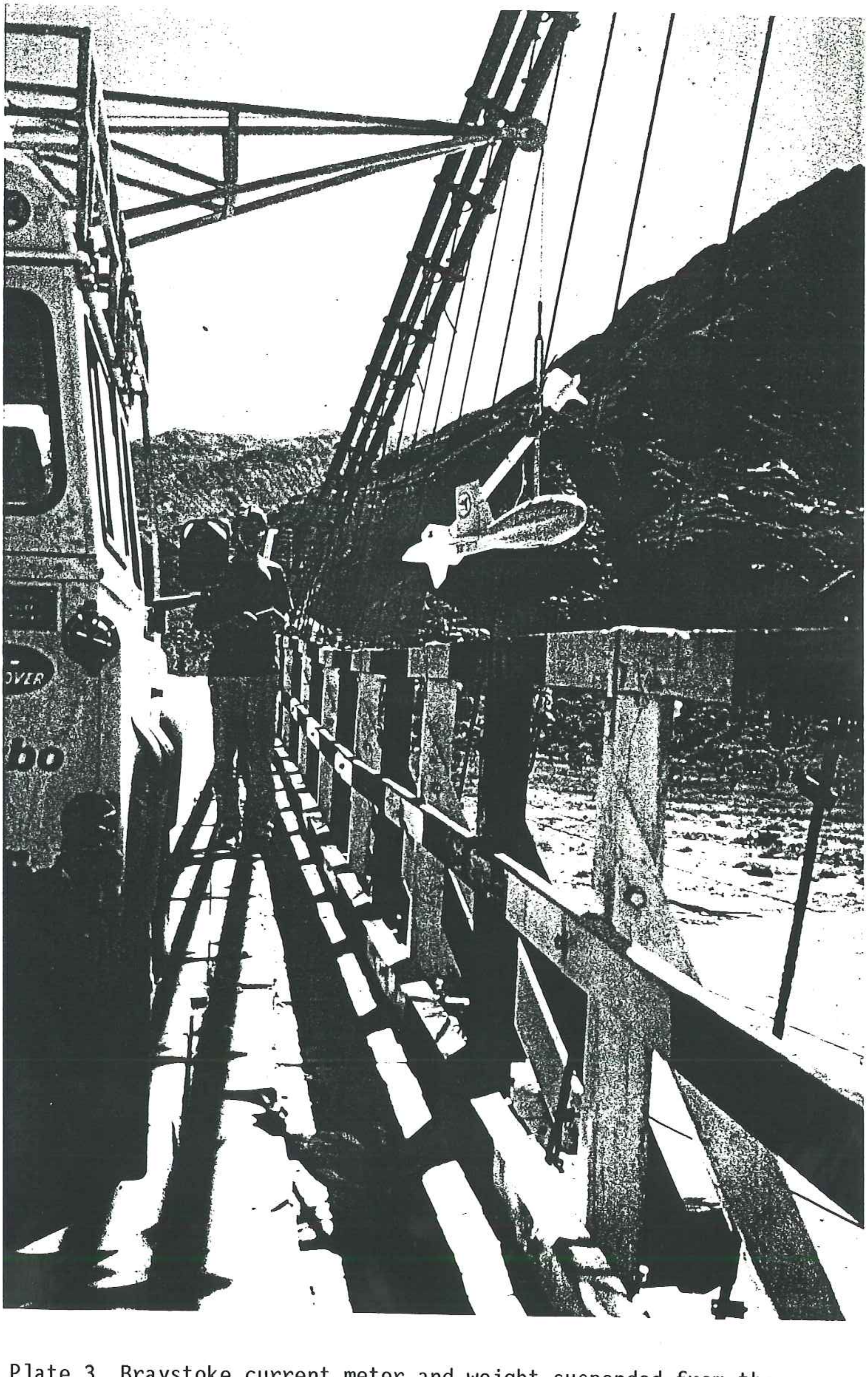


Plate 3 Braystoke current meter and weight suspended from the derrick on the roofrack of one of the SIHP Landrovers at Shigar Bridge, Shigar River, in August 1989.

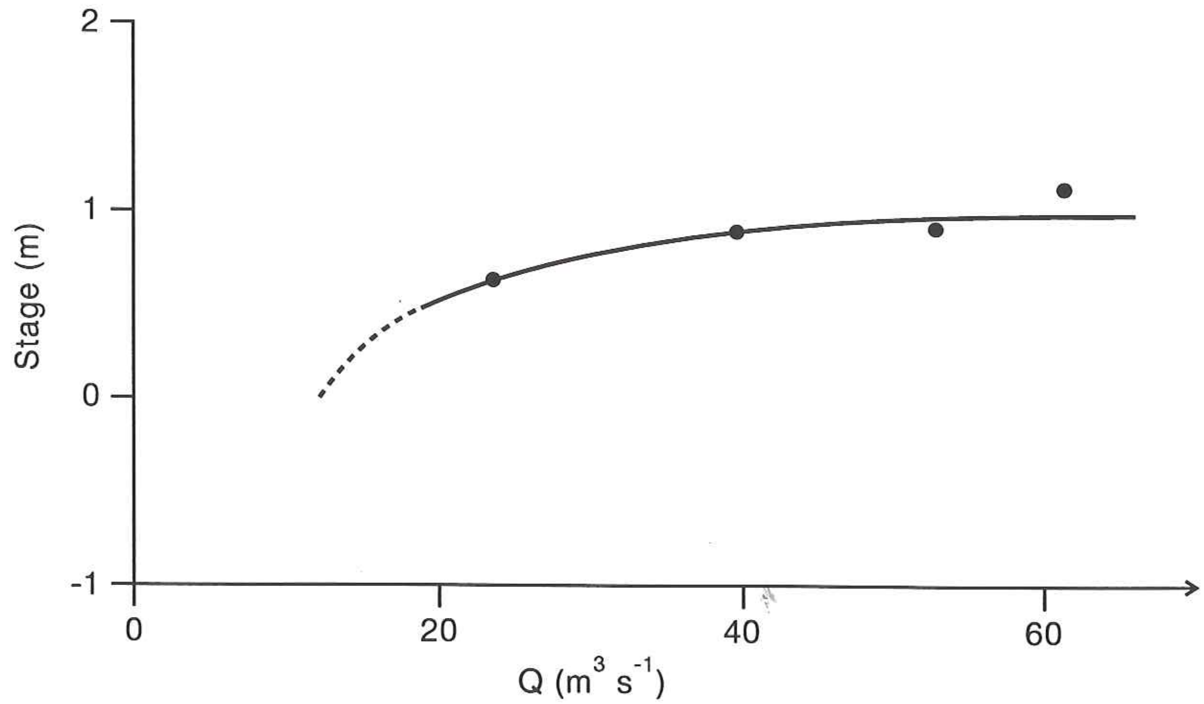


Figure 6. The stage-discharge rating relationship for the Batura River at Batura gauging station valid for June 1989.

8.3 Stage-discharge rating relationships

In the wide rivers of the Karakoram, in which discharge and hence stage fluctuate with a marked diurnal rhythm, the length of time taken to measure depth and carry out velocity measurements at several positions in each of many verticals dispersed over the cross-section means that the discharge changes considerably during a gauging. Fewer verticals spaced more widely, fewer measurements in each vertical or a shorter duration for each velocity measurement period speed the process up but lead to a reduction in accuracy. Verticals every meter across the river with measurements at 0.2 and 0.8 depth formed the standard technique in order to obtain discharge by the velocity-area method.

Shifting beds, changing cross-sections, unusual relationships between velocity and stage in which stage appeared not to change whilst velocity in the channel close to the opposite bank increased obviously, produce stage-discharge curves which needed up-dating during a summer, and which were no longer applicable in the following summer. Where stage boards were destroyed or the retaining fixtures washed away, when low flow next permitted, replacement was not always in the same place. Stream gauging was therefore time consumptive and frustrating.

As an example, the stage-discharge rating relationship valid for June 1989 at Batura is shown in Figure 6. The relationship fitted through four determinations of velocity and area only is:

$Q = 52.48 \text{ stage}^{1.70}$.

8.4 Electrical conductivity of meltwater

Electrical conductivity (EC), a measure of chemical quality of meltwater, was determined with pHOX Instruments meters attached to Sproule cells of carbon electrodes set in resin. Each cell was calibrated against 0.01M K Cl solution, at a known temperature, and the cell constant determined at the beginning and end of a period of immersion. No drift was detected. EC was monitored continuously for as long as possible at each station each year and certainly throughout the summer fieldwork period. Available data for stations and years are indicated in Table 2. Technolog solid state dataloggers were coupled with the conductivity meters and recorded the mV output every 10 minutes as described in 8.1 above.
EC is reported at the measurement temperature (of about $1^{o}C$) and has not been standardised to $25^{o}C$. Total dissolved solids content (in mg L^{-1} is roughly equal to 0.65 x EC (in US cm^{-1}).

Occasionally, short term pulses were observed in the 10-minute EC

Table 2. Measurements of electrical conductivity of meltwaters

River	1987	1988	1989	1990	1991	1992
Batura		x	x	x	x	x
Bualtar	x		x	x	x	
Hunza			x			
Passu			x	x	x	

data, which appear to be another instrumental or logging imperfection. For one 10-minute period, the mV signal falls by up to 20% of the actual level and then recovers to take on the general shape of the curve. A very large (and sudden) but unrecorded change in discharge would be necessary to produce this feature. An example is given in Figure 7. The mV output from the EC monitoring system at Batura on 3 - 4 August 1989 was interrupted twice in 48 hours. It has been noticed elsewhere that the mV signal produced by EC meters can fall and become irregular when the electrode is intermittently out of water. It may be that air bubbles or sediment have temporarily entered the electrode. The respective values were edited and replaced by the default reading before averaging to hourly values.

8.5 Suspended sediment content of meltwater

Epic 1011 portable automatic water samplers (Plate 4) were used to collect samples of between 150 and 200mL of meltwater each hour, 24h every day, during the ablation season at sites on the rivers draining from Batura, Passu, and Barpu-Bualtar glaciers. Care was taken to ensure that the inlet hose remained submerged in the river at times of low flow but was sufficiently far from the bed not to acquire silt from the bed and become clogged.

Every sample was filtered under vacuum through an individually pre-weighed Whatman No. 1 filter paper circle, before being sealed in an individual polyethylene bag, in which the filter together with sediment was returned to the laboratory in Manchester. Dried at $105^{o}C$ under a Mettler infra-red balance attachment, each filter and sediment was weighed, and the quantity of sediment determined gravimetrically, by subtraction of the weight of the dry filter paper. Concentration of suspended sediment is obtained from this weight and the volume of the sample which was measured at the time of collection.

8.6 Hydrometeorological measurements

As described earlier, in general, weather stations at low elevations, in valleys or at the margins of mountain massifs are not representative of conditions high in glacierised mountains. In the Karakoram, additionally, valley floors are warm and arid, attributed to the tendency for subsidence in the slope wind circulation (Barry 1992), the so-termed 'Troll' effect, and are very different climatically from the high mountain environment.

The basin of Passu Glacier was selected for further investigation in

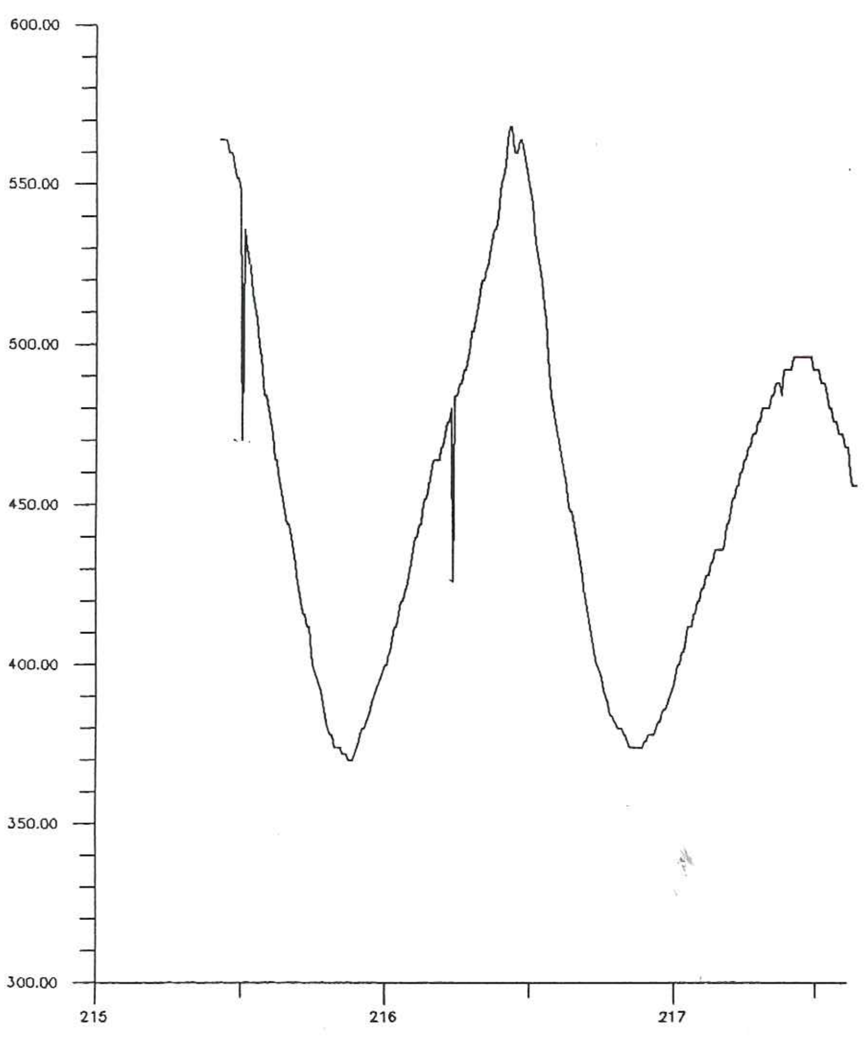
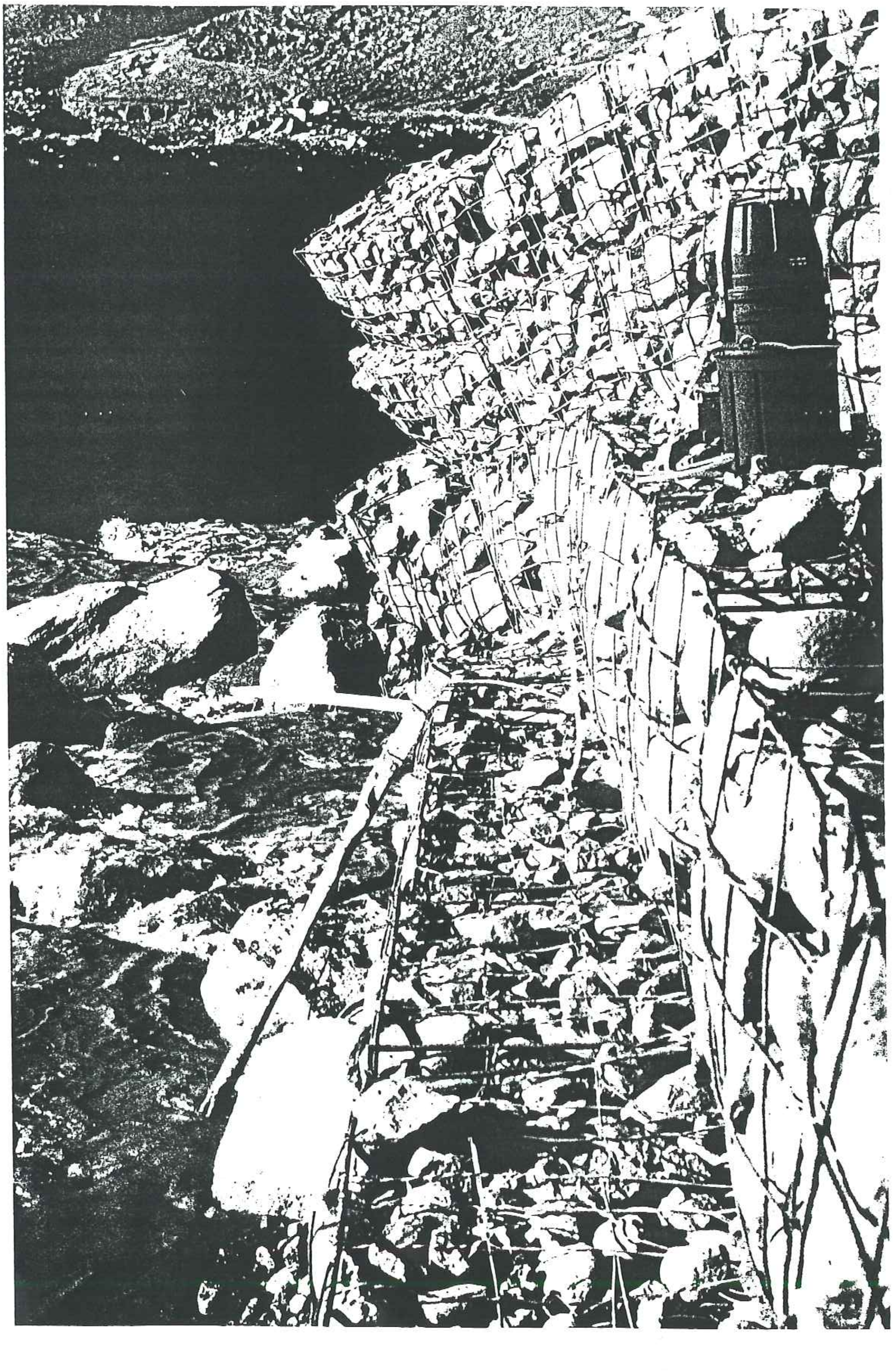


Figure 7. Sudden short-term fluctuations in the diurnal rhythm of the mV signal from the EC recording system at Batura gauging station on 3 (day 215) and 4 August (day 216) 1989.



<u>Plate 4</u> An EPIC sampler on location at Batura Glacier gauging station. Note that the gabion has been undermined by erosion of the bank by the meltwater.

order to locate suitable sites for meteorological stations. The basin has several advantages, not least that the meltwater river was also in the gauging and water quality measurement programme. It is accessible through a range of elevations and while relatively compact in terms of Himalayan scale extends over 5km vertically. Three sites were chosen:

1. Passu glacier terminus
   This site at 2700m, 150m above the gauging station, is amongst irregular former right lateral moraine, protected somewhat against katabatic winds.

2. Passu Gahr
   At 3500m a. m. s. l. above the right margin of the glacier.

3. Patundas
   At 4220m, on the divide between Passu and Batura glaciers.

All three stations were equipped with Carleton Instruments thermohydrographs placed inside Stevenson screens in 1989. Calibration against certificated thermometers was periodically undertaken. Themistors were used at Passu terminus station, shielded in the Stevenson screen. A Kipp and Zonen pyranometer was used to measure incoming global radiation at Passu terminus in late summer 1989, after a short period at Batura glacier gauging station.

In 1990 and 1991 only the terminus stations operated. A tipping bucket rain gauge was added in 1992 at Passu terminus.

9. Results: data collected

9.1 Long continuous high quality hydrometric data

Since one of the objectives of the project was to collect basic data concerning the hydrology of glacierised areas in the UIB, it was intended to collect long continuous series of measurements which would enable characterisation of diurnal rhythms and seasonal variations of water quality and quantity in meltwater rivers, and to assemble those series in a suitable form for direct use in models linking thermal and precipitation inputs with runoff. Those data sets which meet the requirements of length (several months), quality (few breaks in the continuity, good stage-discharge relationships if available) and others which either provide information for short periods from a wider geographical area, or which are collected at the same station or in the same basin as extended data sets or relate to them are listed in the appendices to this report.

Data meeting these criteria have been reduced to mean hourly values throughout all the periods for which they are available and a standardised database assembled as 'hydrological yearbooks', listings of the hydrological and hydrometeorological information collected each field season, following usual hydrometric practice. These data are then directly avaiable for (1) modelling purposes, (2) production of graphical output and (3) further reduction to daily mean and range values.

9.2 Structure of the data tables

The tables are structured in repeating units as follows:

```
27  6 1990   178
 999.999 999.999 999.999 999.999 999.999 999.999 999.999 999.999 999.999   3.819   4.071   3.833
   4.185   4.148   4.210   3.319   3.247   4.695   4.445   4.135   4.052   4.595   4.325   4.105
28  6 1990   179
   4.429   4.329   4.362   4.455   4.376   4.315   4.057   4.252   3.733   3.630   3.235   3.575
   3.395   3.458   3.925   3.526   3.674   4.205   3.090   4.563   8.290   5.175   5.295   4.785
29  6 1990   180
   4.570   4.386   4.100   3.790   3.920   3.685   3.210   3.420   0.695   3.905   3.465   4.115
   3.671   4.374   3.968   3.605   3.790   3.890   4.042   3.479   4.260   4.691   5.286   5.036
```

The values in a unit refer to:

Day month year Julian day

followed by average values for the 24 hourly periods of the day defined as:

```
00.00-00.59h 01.00-01.59 02.00-02.59 03.00-03.59 04.00-04.59 .... 08.00-08.59 09.00-09.59 10.00-10.59 11.00-11.59
12.00-12.59  13.00-13.59 14.00-14.59 15.00-15.59 16.00-16.59 .... 20.00-20.59 21.00-21.59 22.00-22.59 23.00-23.59h
```

In the case of suspended sediment content of meltwaters, the repeating unit consists of:

Day month year Julian day

and instantaneous measurements obtained every hour, on the hour, as follows:

```
00.00h  01.00  02.00  03.00  04.00  05.00  06.00  07.00  08.00  09.00  10.00  11.00
12.00   13.00  14.00  15.00  16.00  17.00  18.00  19.00  20.00  21.00  22.00  23.00h
```

Missing data are represented by 9 as 9.9, 999.9(9) 999.99(9) or 9999.99 as the default value, according to the number of digits and decimal places in the data set.

9.3 Gaps in the records

Inevitably, gaps in the time series have arisen, generally as a result of equipment or battery failure. The nature of the rivers also contributes. Large scale seasonal fluctuations of water level make difficult the permanent securing of station immersibles in meltwater rivers, particularly where the angle of the banks of the river is low or ill-defined. Fixtures which are placed too low are removed if not by summer flows by occasional unpredictable outbursts of water. One outburst from Passu Glacier, unusually in winter (in February 1991) not only destroyed the UMAGP site, but also undercut a pier of the bridge carrying the Karakoram Highway, and going on inundated part of the village. Other fixtures may be left high and dry at the end of the ablation season not just by low flow, but by migration of the thin remaining thread of discharge in winter to differing positions across the boulder strewn bed. Fairly regular visitation of sites by hydrologists minimises interruption of the continuous record.

9.4 Appraisal of the data collection programme

The field monitoring programme in 1989 started in early May and ended in mid-September. By the time the equipment had been prepared in Islamabad and transported to the Northern Areas, the melt season had already commenced. By comparison with alpine locations, the field seasons would have to be elongated starting in April and ending in October for full coverage of the melt season in the Karakoram. Also, in 1989, the number of basins investigated was too large, and the spatial spread of the stations too wide, although permitting conclusions to be drawn on the extent to which the various glacierised basins responded in a similar way to the regional climate. The decision to concentrate effort at Batura and Passu glaciers in 1990 enabled better quality data to be collected at lower cost. The measurement period in 1990 extended from April to October and produced what is certainly the best set of glacier hydrological data for high Asia to date. Lower cost expeditions in 1991 and 1992 concentrated on Batura also, and produced quality information in 1991. The aim was to examine year to year variations in runoff from glaciers, as WAPDA measurements on the Hunza at Dainyor Bridge from 1966 to 1981 suggested that flows could vary between 30 per cent below the 16-year mean to 30 per cent above. Unhappily for the hydrometric network, but of importance in the question of year to year variation in runoff, rain commenced over the Karakoram on 1 September 1992. A storm in the morning of 8 September increased the intensity of rain, which then turned to snow before drizzle took over on 10 September. In the Braldu basin, heavy rain and snow at higher elevations occurred on 9 - 10 September (Hewitt 1993). The ensuing floods, thought to be about the 100 year event (Bohle and Pilardeaux 1993), destroyed the gauging stations and equipment, including washing away the data with the loggers.

10. Characteristics of meteorological variables

10.1 Global incoming short-wave radiation

An example of the detail contained in 10-minute interval radiation data is shown in Figure 8, for a period of six days in August 1989. These data were recorded at Passu Glacier terminus meteorological station. On 23 August, the impact of cloud interception on radiation was almost absent in the morning, but on all other days shown, only occasionally was radiation able to rise to levels that might be expected for the appropriate time of day and year at this latitude and elevation. The effect of averaging the ten-minute data at the hourly level is clear from Figure 9, producing a smoother curve; this level of temporal resolution is appropriate for hydrological modelling and all the data have been reduced to the hourly level.

Between 18 July and 1 August 1989, the pyranometer was located in the proglacial outwash area of the right bank of the Batura River about 1km from the glacier snout. On 1 August the instrument was repositioned at the Passu Glacier terminus meteorological station alongside the thermohydrograph. Comparison of the curves of measured radiation in Figures 10 and 11 indicate that the two locations receive very similar diurnal patterns of radiation flux, both being in broad valleys opening to the Hunza valley which, although surrounded by high mountains, is wide where these basins coalesce. There is little seasonal trend in radiation between mid-July and late August, although maximum levels of daily mean radiation reached before mid-August were not subsequently attained in 1989 (Figure 12).

10.2 Air temperature

Air temperature recorded at hourly intervals by a screened thermohydrograph at the Passu Glacier meteorological station in May through August 1989 is plotted in Figure 13. Marked diurnal temperature fluctuations of usually at least 5 and up to 15 degrees are indicated. The diurnal temperature rhythm is asymmetrical, the air warming up faster in the morning with the onset of radiation than cooling during the night.

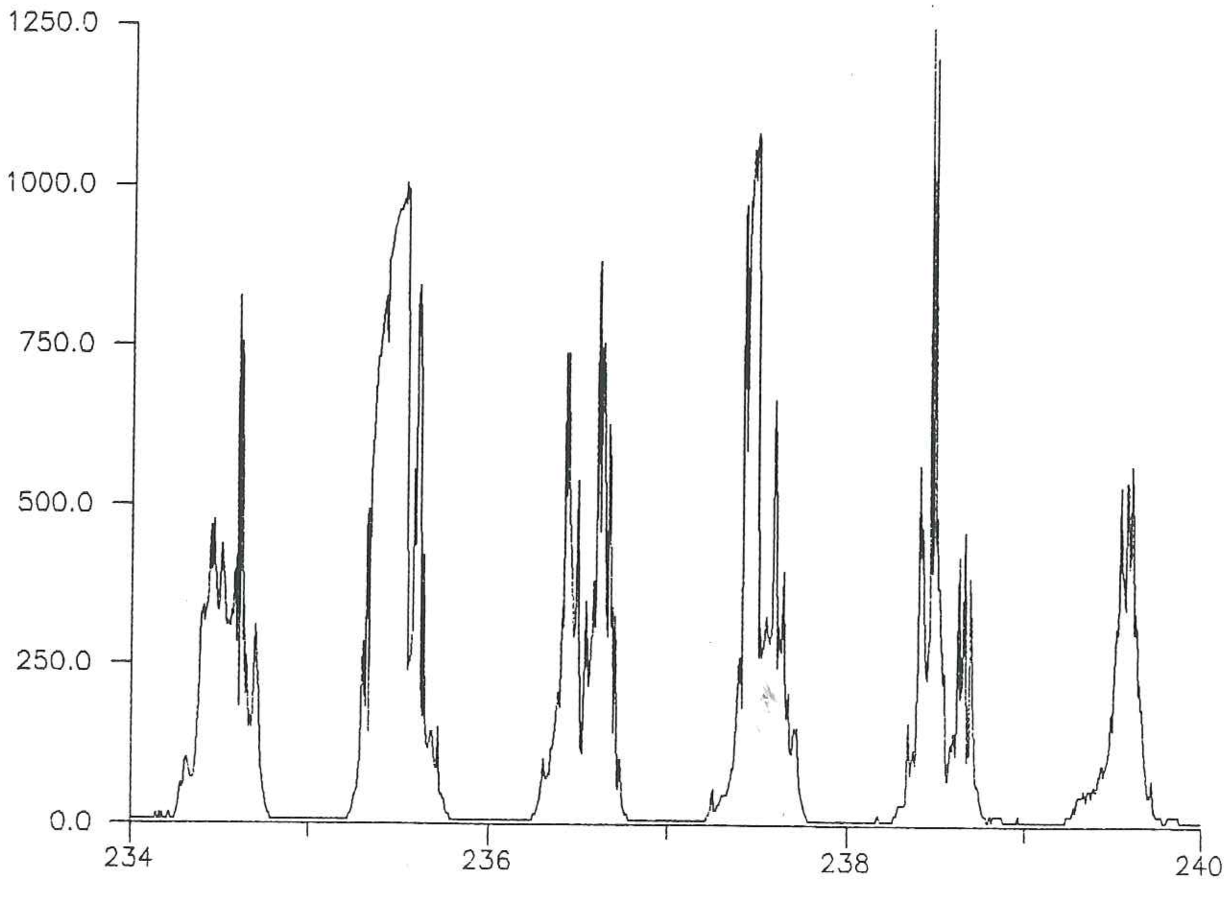


Figure 8. Global short wave radiation (W m^{-2}) recorded at 10 minute intervals at the meteorological station at Passu Glacier terminus between 22 (day 234) and 27 August (day 239) 1989.

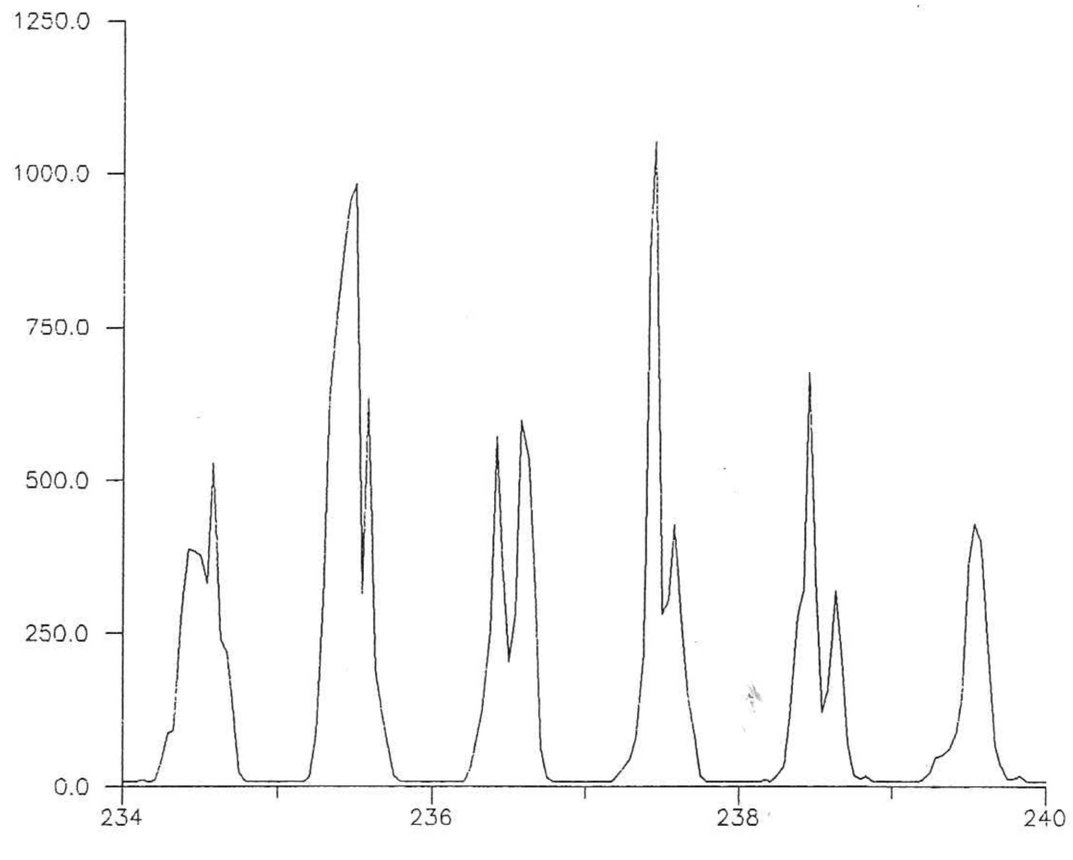


Figure 9. Hourly average short wave radiation (W m^{-2}) at the meteorological station at Passu Glacier terminus between 22 (day 234) and 27 August (day 239) 1989.

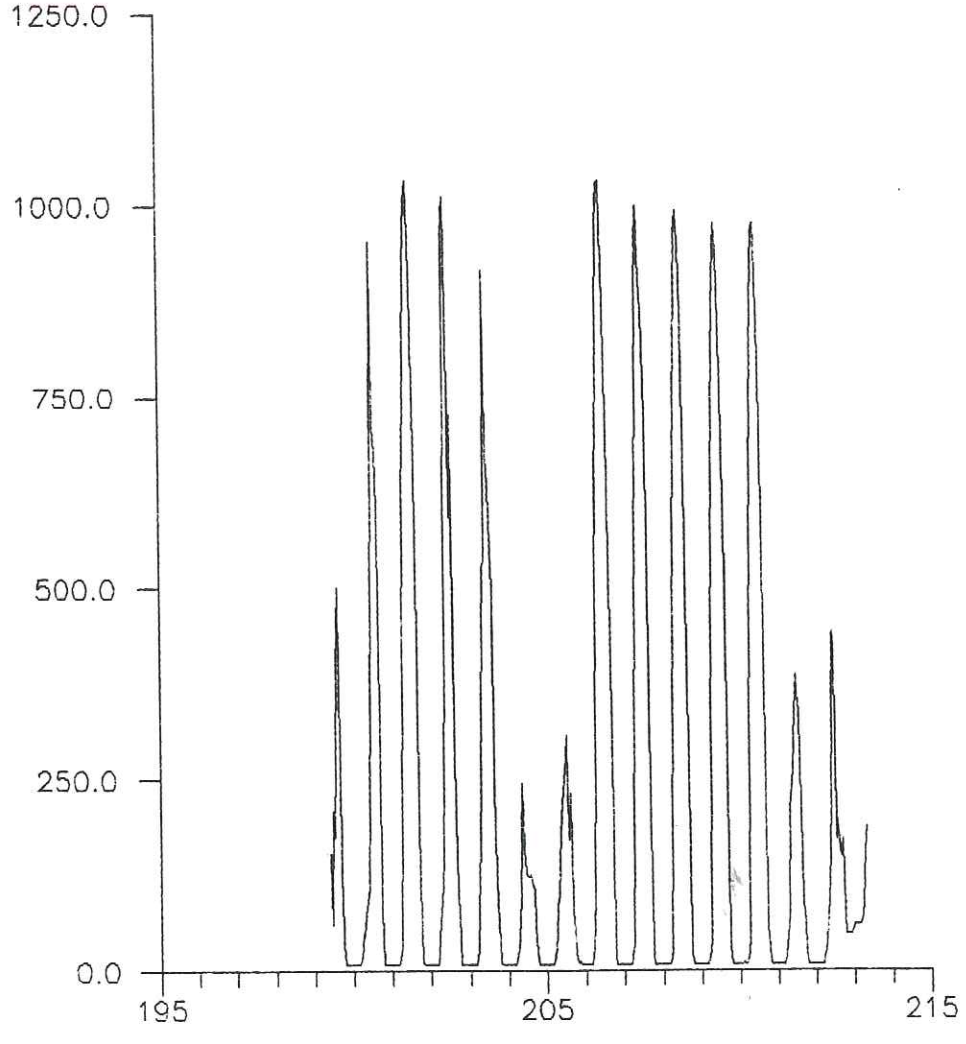


Figure 10. Hourly average short wave radiation (W m^{-2}) at the meteorological station at Batura River gauging station between 18 July (day 199) and 1 August (day 213) 1989.

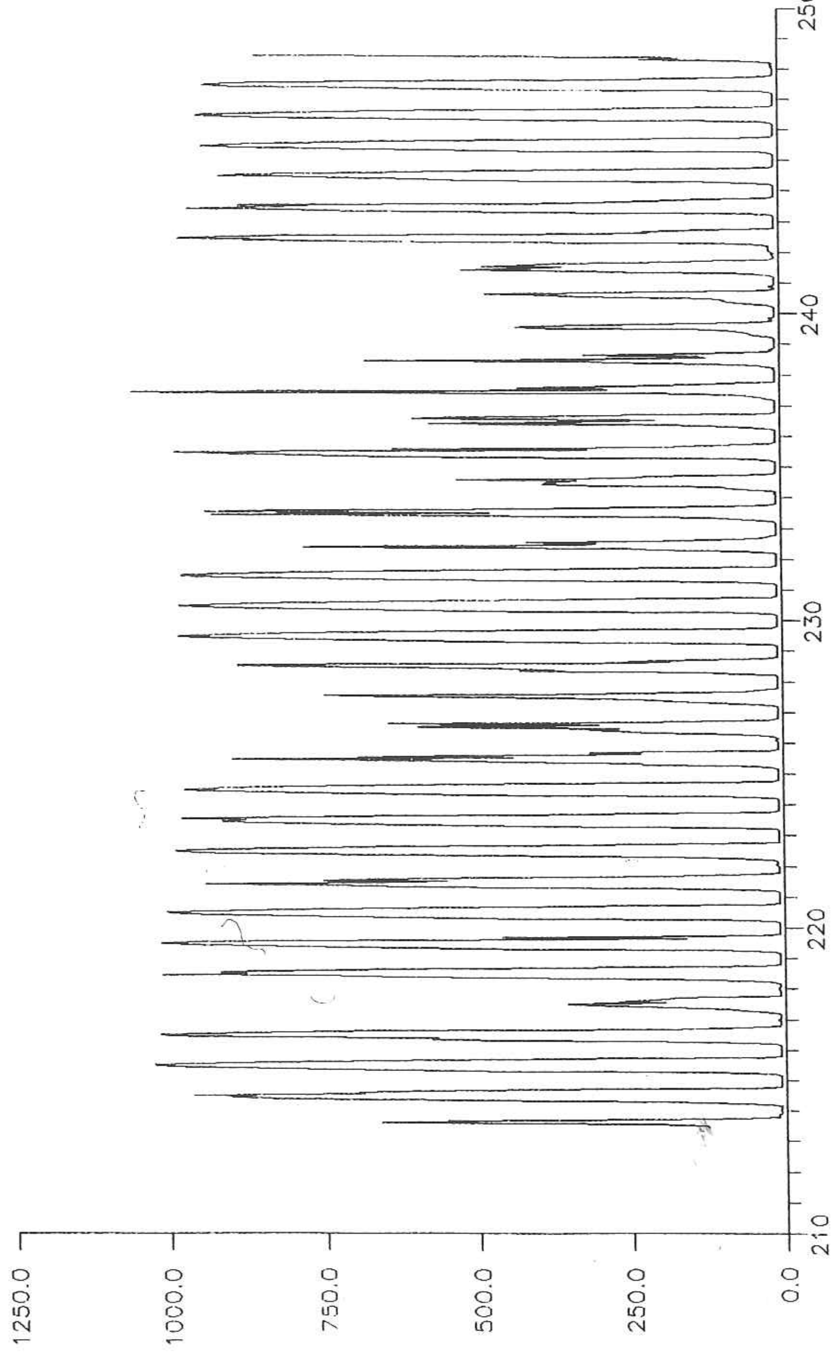


Figure 11. Hourly average short wave radiation (W m^{-2}) at the meteorological station at Passu Glacier between 1 August (day 213) and 5 September (248) 1989.

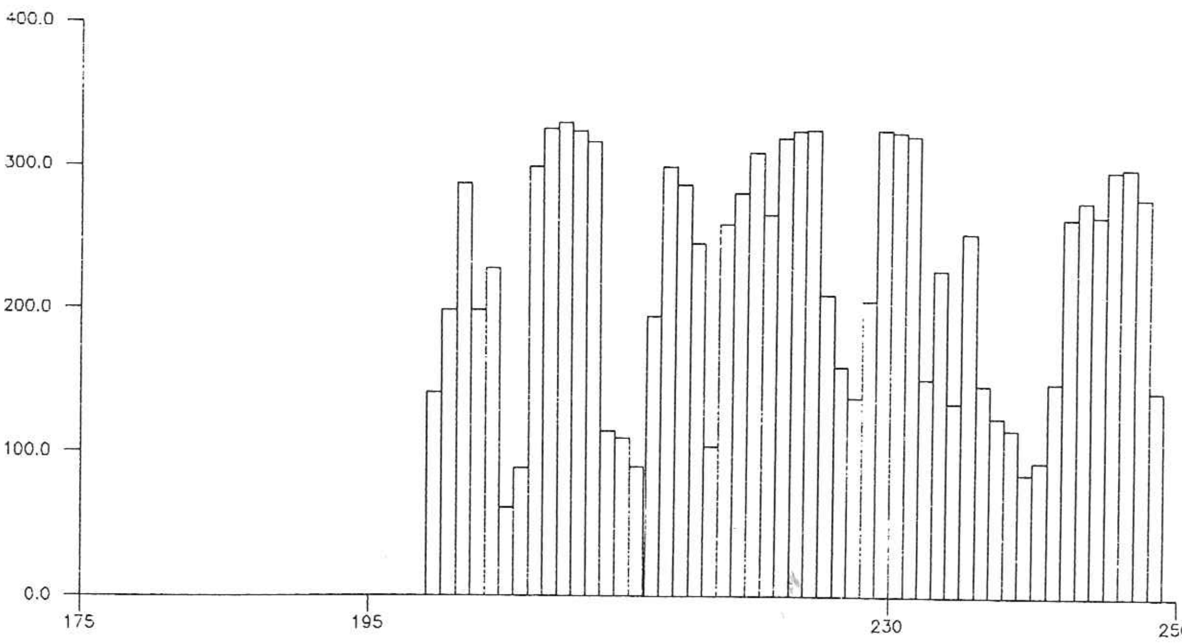


Figure 12. Combined record of daily mean short wave radiation (W m^{-2}) at the meteorological stations at Batura River gauging station and Passu Glacier terminus in 1989.

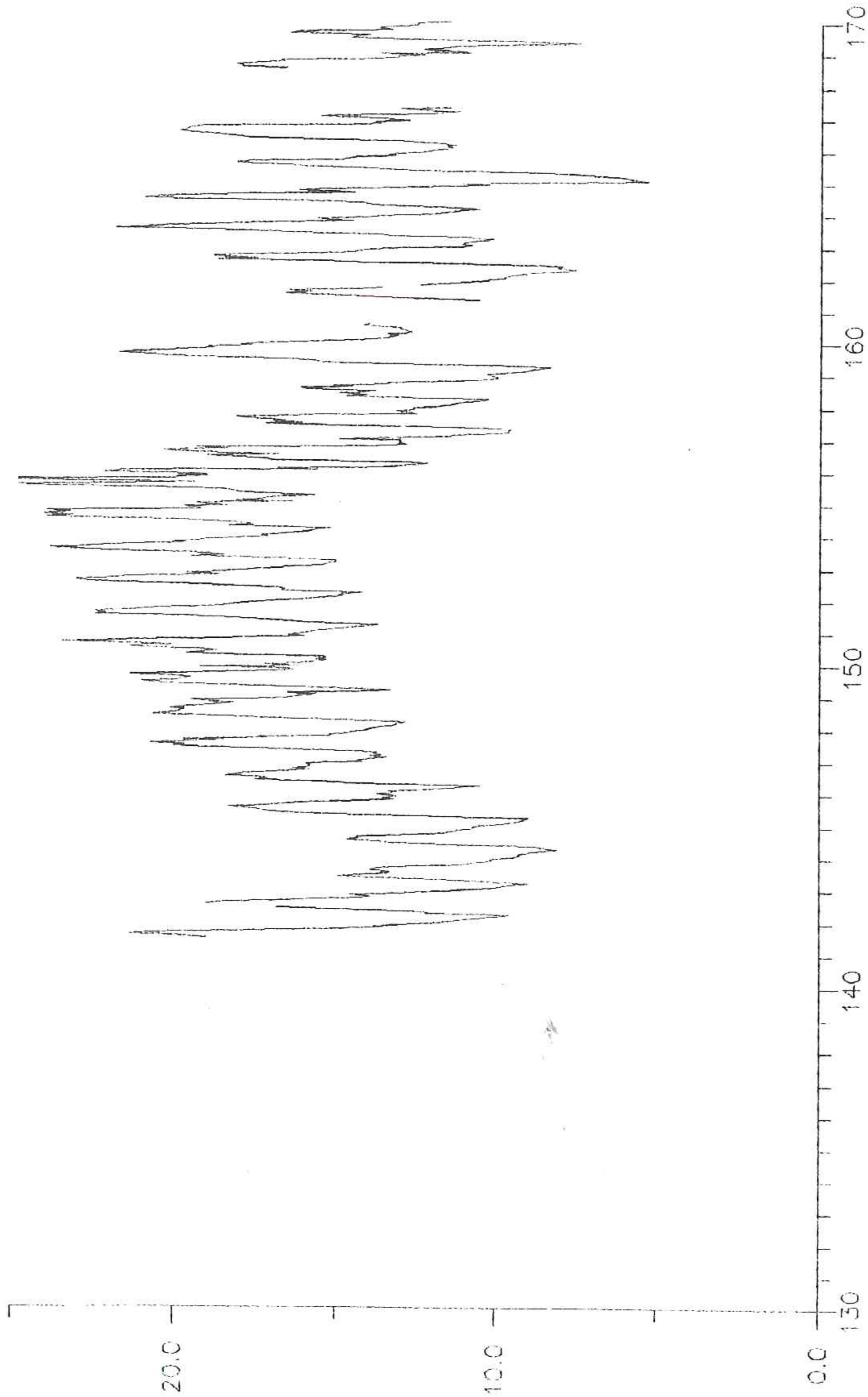


Figure 13. Air temperature (^{0}C) recorded each hour in the Stevenson screen at Passu Glacier terminus meteorological station from 21 May (141) to 31 August (243) 1989.

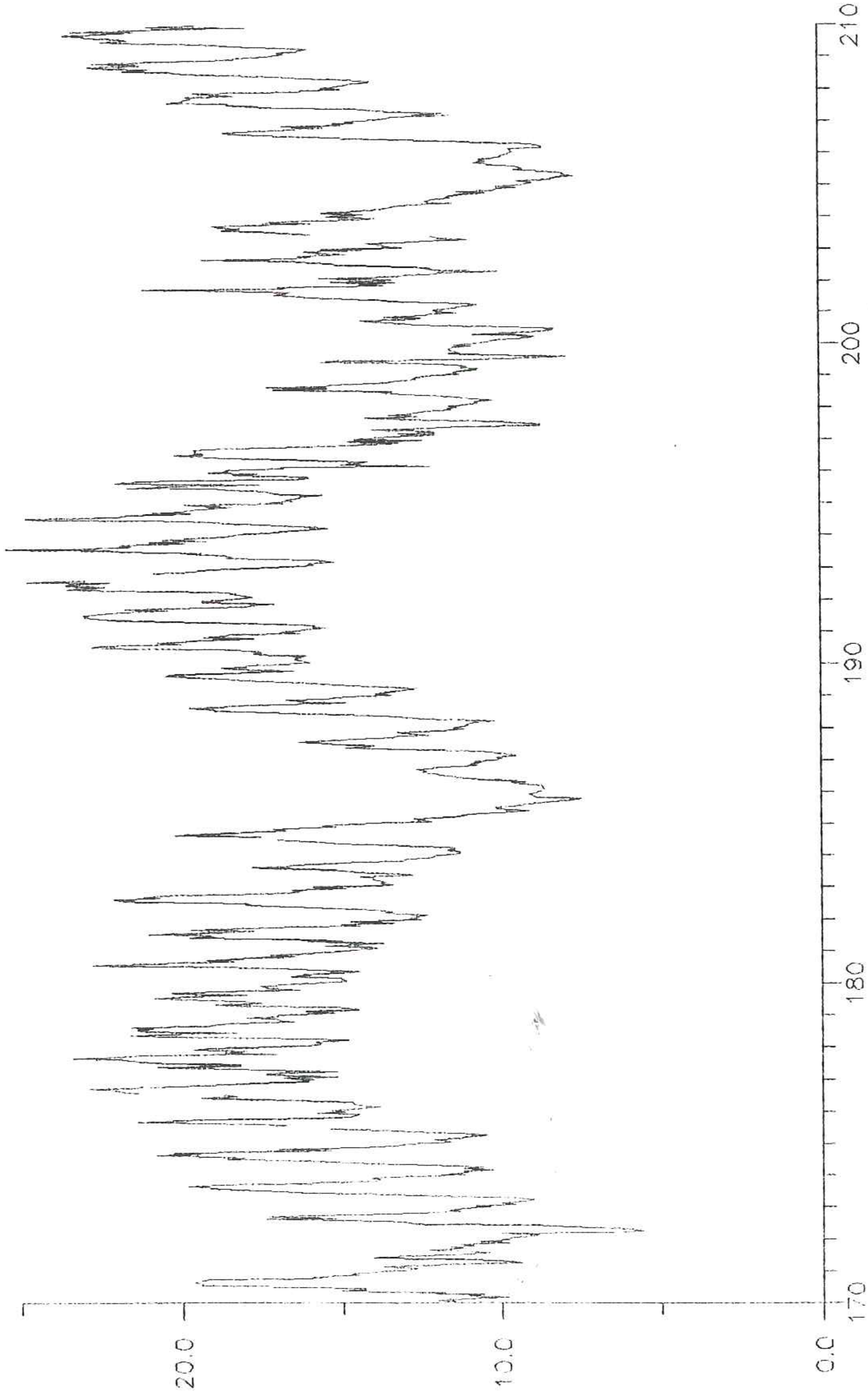


Figure 13 (continued). Air temperature (^{0}C) recorded each hour in the Stevenson screen at Passu Glacier terminus meteorological station from 21 May (141) to 31 August (243) 1989.

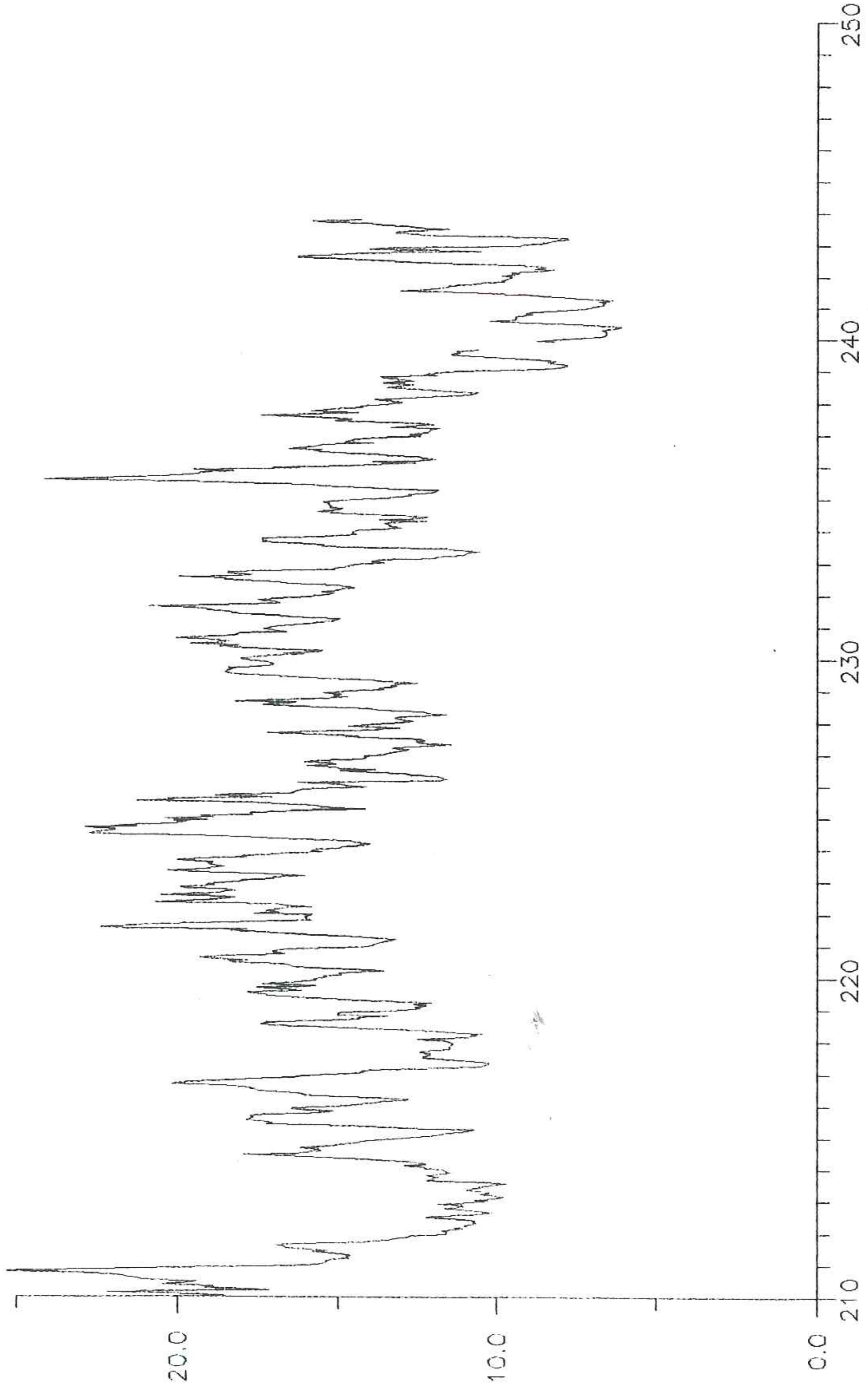


Figure 13.(continued) Air temperature (^{0}C) recorded each hour in the Stevenson screen at Passu Glacier terminus meteorological station from 21 May (141) to 31 August (243) 1989.

There are sequences of warmer and cooler periods, often of 10 or 12 days when the underlying temperature on which diurnal cycles are superimposed generally rises, and then falls for several days. Such sequences are brought out by a plot of the series of daily mean air temperatures as in Figure 14, in which the data given in Figure 13 for Passu Glacier terminus are shown.

10.3 Lapse rate of air temperature

Both the actual temperatures and the diurnal ranges of temperature at the high elevation stations are reduced by comparison with those at Passu Glacier terminus, to a greater extent at the elevation of Patundas than at Passu Ghar (see Figure 15). The pattern of variation through time at diurnal, sequence and seasonal timescales is however closely parallel as plots of daily mean air temperature at the three stations in 1989 indicate (Figure 16). Daily mean temperatures in summer were below zero Celsius on only 2 days in 90 during the summer months of 1989 at 4200m, suggested that melting of glaciers in this area continues 24h a day to at least that elevation, although radiation energy input obviously increases the rate of melt during daylight hours, which account for 14-15 hours of each day at this season.

The lapse rate is highly variable, and changes with elevation, season, and during the diurnal energy input cycle. Lapse rates also differ between clear sky and cloud-covered conditions (Figure 17). The mean value for 1989 was $-6.1\ ^{o}\,C\ km^{-1}$, not too far removed from that indicated between Gilgit and Mishgar.

10.4 Degree days

The sum of positive degree days provides a useful indication of energy availability for melt in snow and ice hydrology. The daily total degree days for Passu Glacier terminus and Patundas are shown in Figure 18. The number of degree days is greatly reduced at the higher elevation but in July through September the records show considerable similarity at least in the pattern of higher and lower energy episodes. Energy input at high elevation starts much later, at least a month behind the glacier snout, and falls earlier, suddenly, at the start of September.

10.5 Relationships amongst climate variables

Relationships amongst climatic variables are of interest in that it may be possible to use one variable only to characterise the energy availability for melting. Even so, one station at the lower end of a basin is unlikely to reflect cloud cover variations for example at

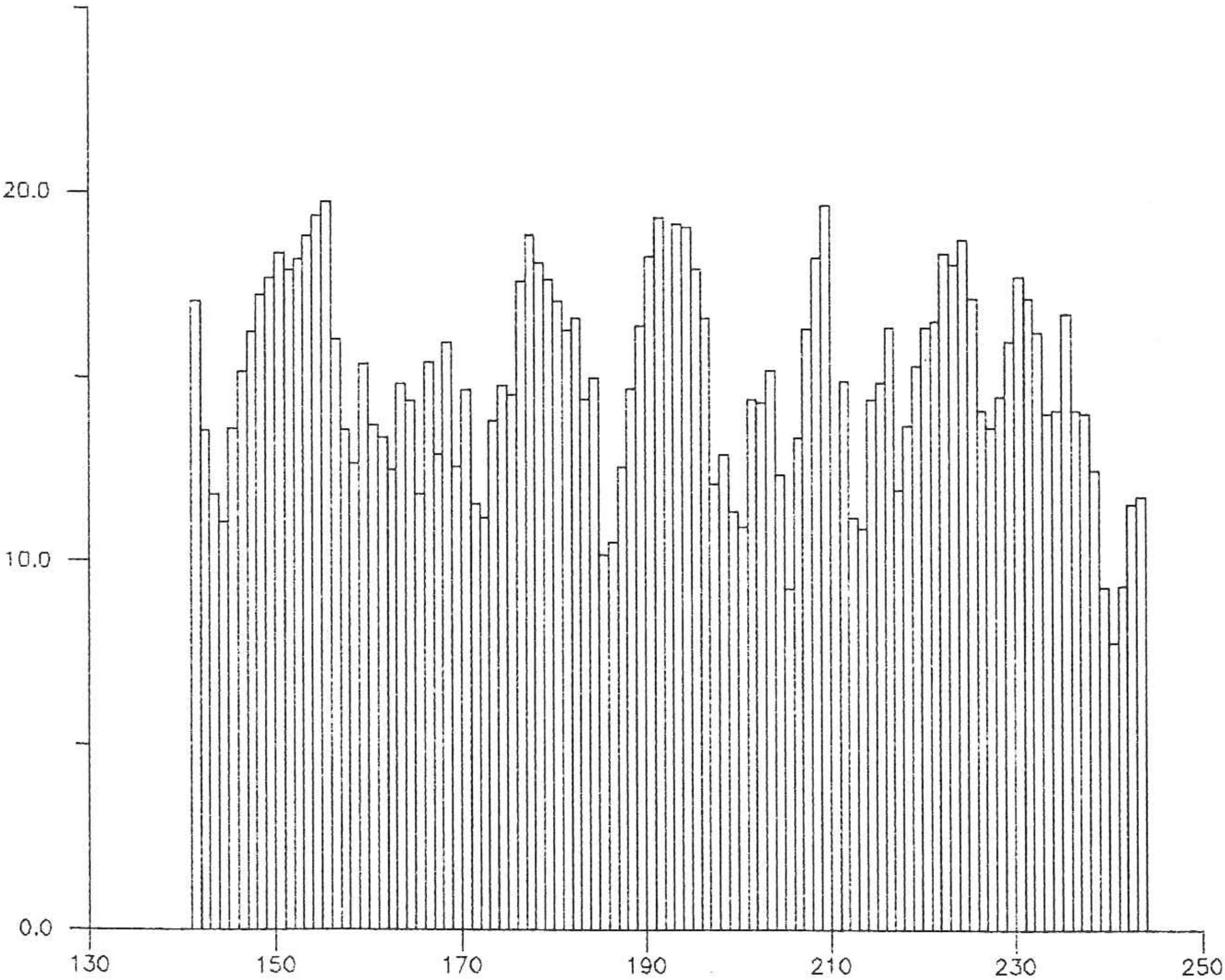


Figure 14. Daily mean air temperature (^{0}C) at Passu Glacier terminus meteorological station in 1989.

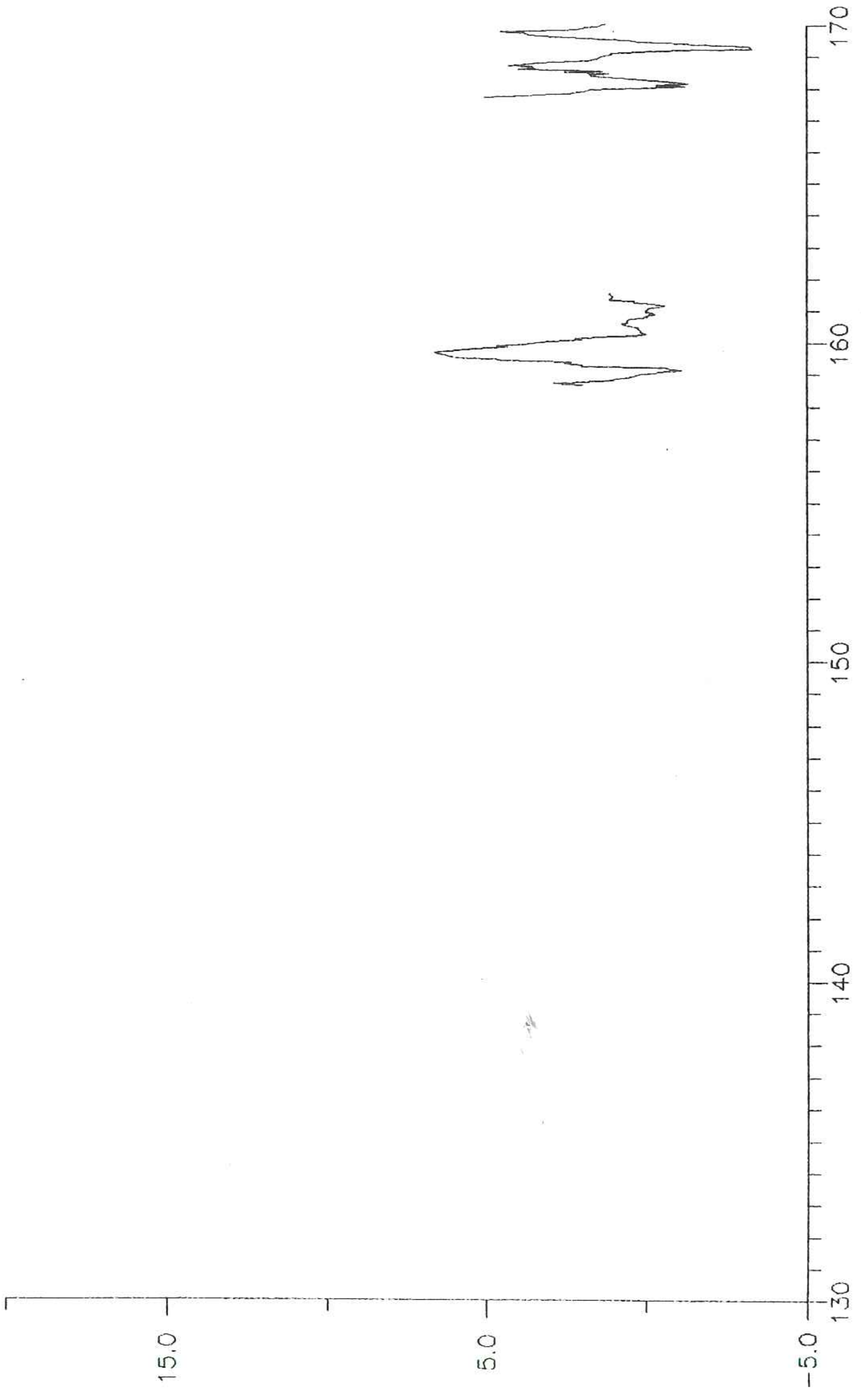


Figure 15. Air temperature (^{0}C) recorded each hour in the Stevenson screen at Patundas meteorological station from May to 31 August (243) 1989.

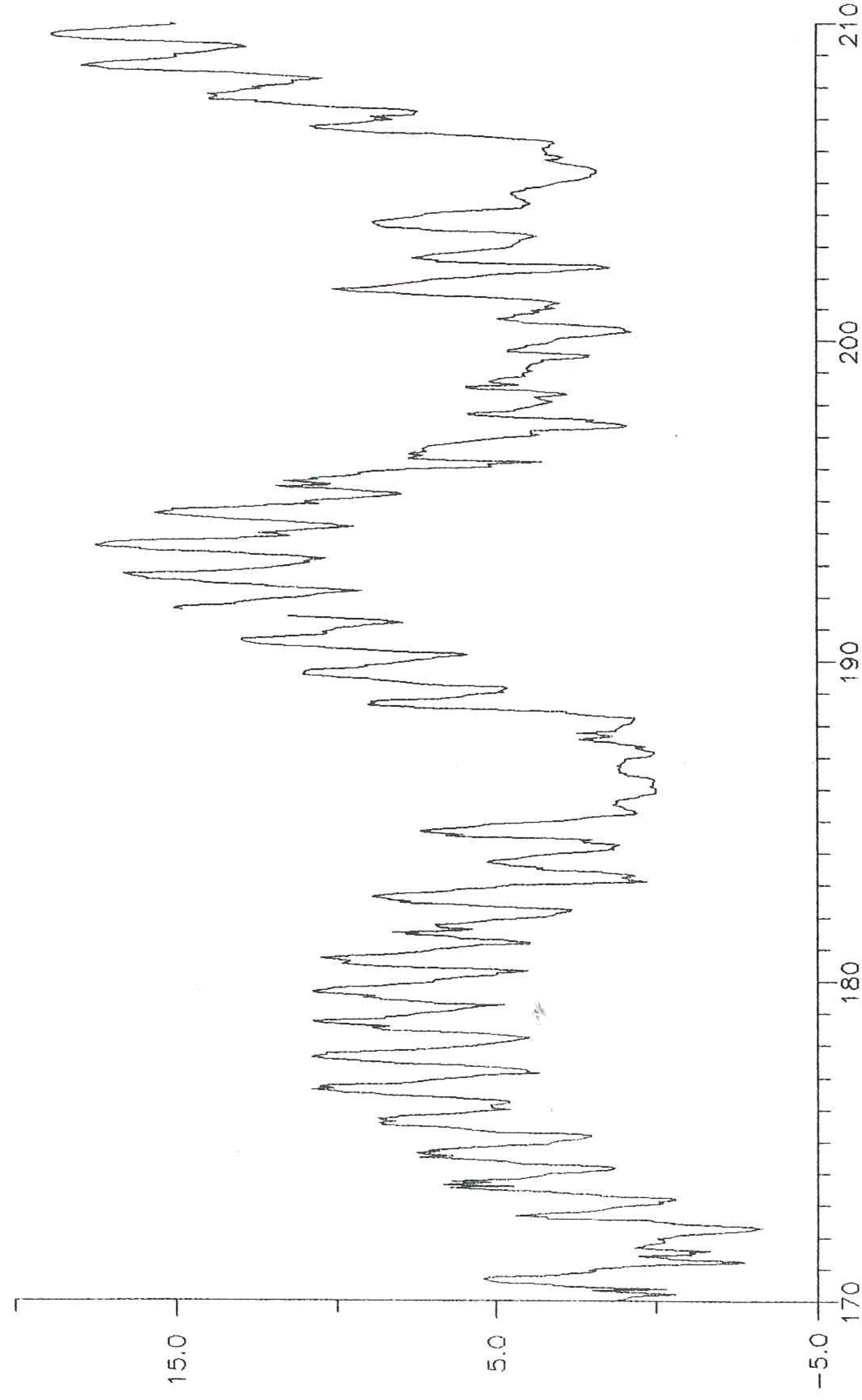


Figure 15 (continued). Air temperature (^{0}C) recorded each hour in the Stevenson screen at Patundas from May to 31 August (243) 1989.

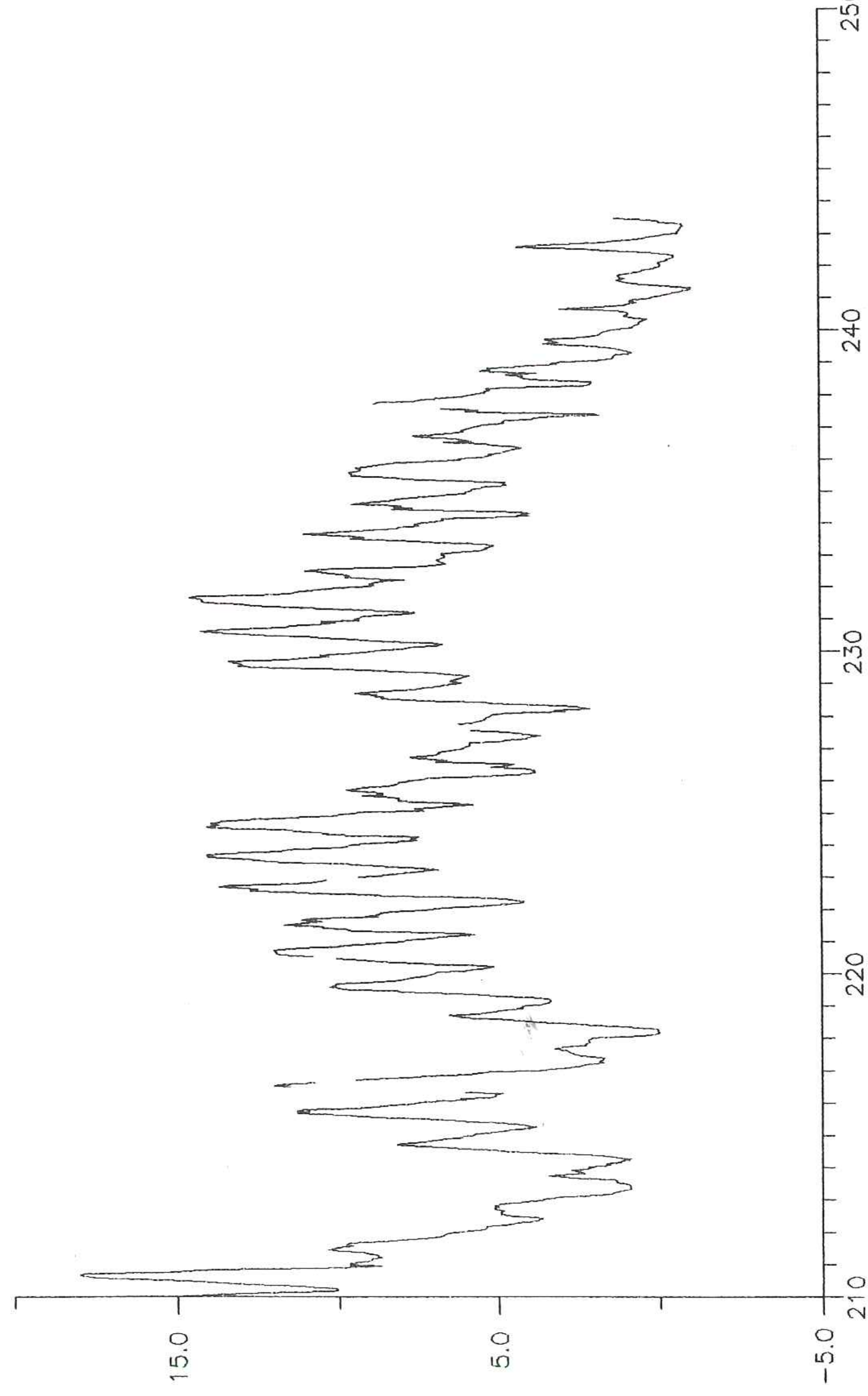


Figure 15.(continued) Air temperature (^{o}C) recorded each hour in the Stevenson screen at Patundas meteorological station from May to 31 August (243) 1989.

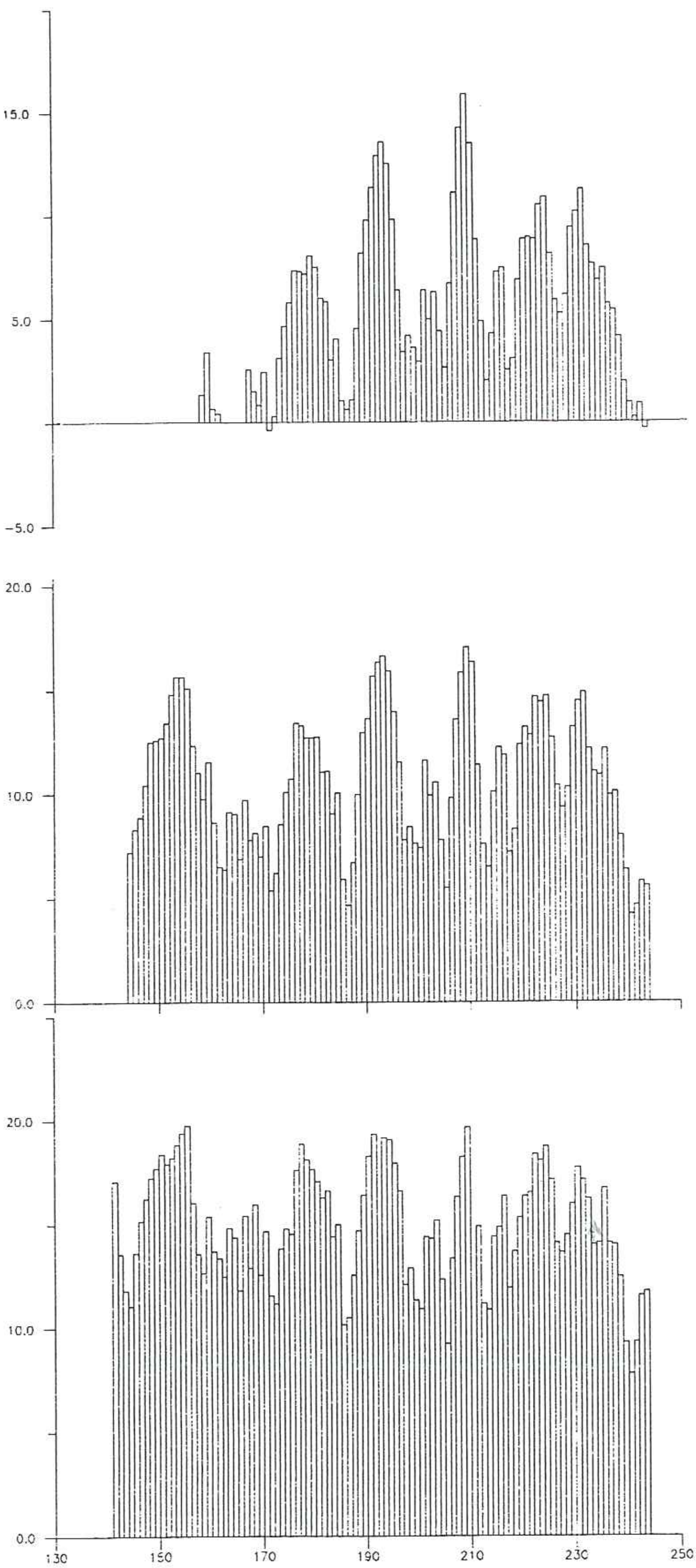


Figure 16. Daily mean air temperature (^{o}C) at Patundas (upper), Passu Ghar (middle) and Passu Glacier terminus meteorological station (lower) in 1989.

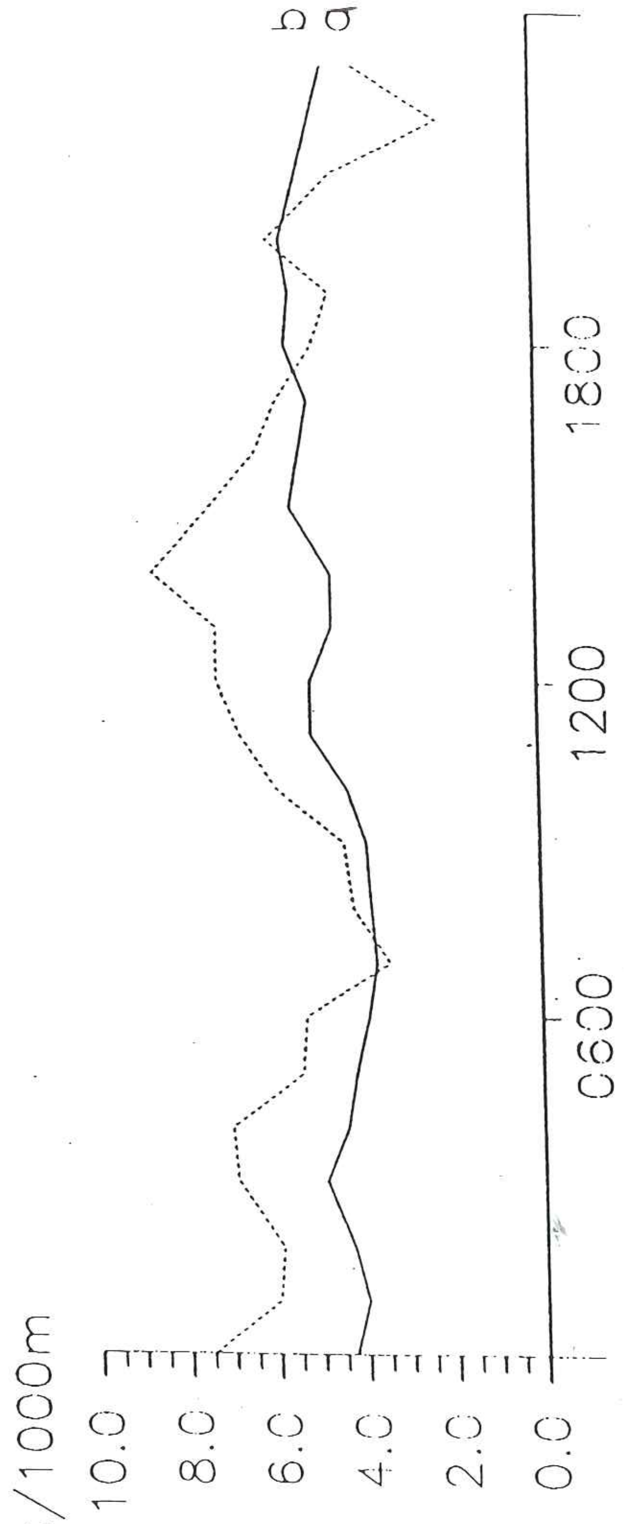


Figure 17. Lapse rates between at Patundas and Passu Glacier terminus meteorological station through 24 hour periods under (a) clear skies and (b) cloud cover.

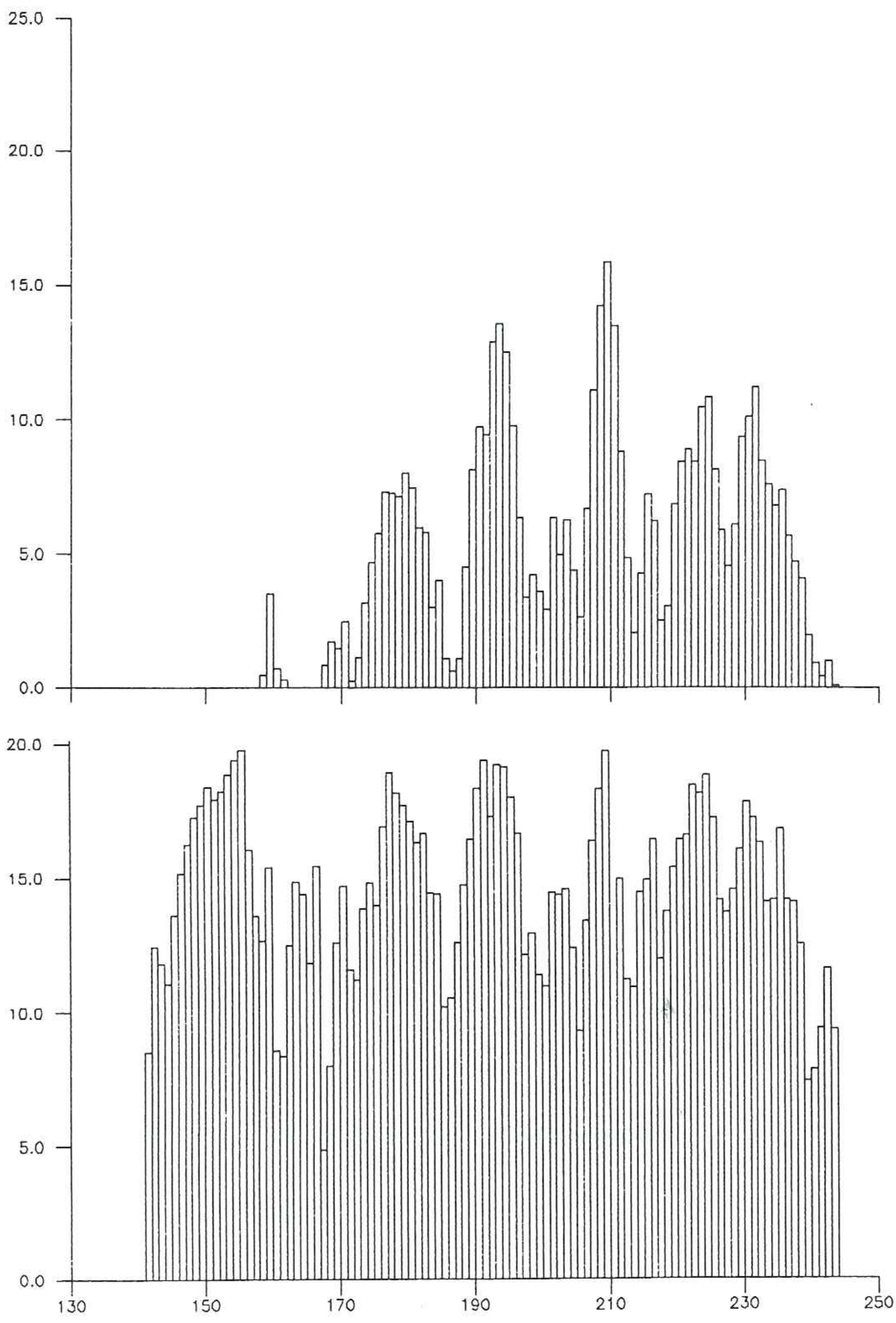


Figure 18. Positive degree days recorded at Patundas and Passu Glacier terminus meteorological stations in the ablation season of 1989.

high elevation. There is a good correlation between air temperature and radiation at Passu terminus, which improves when the air temperature at Patundas is substituted ($r = 0.88$). Daily temperature range provides the best relationship with radiation at Passu Glacier terminus (Figure 19). Diurnal range of temperature is therefore a useful surrogate indicator of radiation in high mountain areas. Clear days have greater temperature ranges than those which are cloudy as temperatures rise quickly in response to radiation input and then fall sharply at night when skies are cloud-free. Conversely, cloud reduces incoming radiation and hence temperature by day, but back radiation is prevented at night so heat is retained and air temperatures are maintained at night.

The impact of radiation input on temperature is apparent from the climatic data recorded at Passu Glacier terminus in 1990 (Figure 20).

10.6 Precipitation

Precipitation and radiation are strongly inversely linked, as in the period 16 - 21 August 1992 shown in Figure 21. With respect to melting snow and ice, not only is radiation reduced when precipitation is actually falling, but also when the precipitation is snow and albedo is raised, and much of the subsequent radiation is reflected. Unfortunately, measures of precipitation at low elevation are neither a guide to whether precipitation has fallen on high ground (as precipitation at high altitude often occurs in the Karakoram when the valleys are dry) nor an indicator of the amount at high elevation. Actually, a dusting of snow persisting in summer may have as great an impact on melt as several centimeters of snow as it is the 'whiteness' of the surface not the depth or water equivalent which is important.

11. Runoff from glacierised basins in the Karakoram

11.1 Characteristics of the basins

Characteristics of the glacierised basins are as follows:

Batura	60.05% glacierised	649.10 km^2
Passu	60.49%	110.79
Hunza	28.46%	13 872.46

Batura Glacier itself accounts for 10% of the ice and snow covered area of the Hunza basin above Dainyor Bridge, to which gauge the above characteristics for the Hunza refer. It might therefore be expected that the patterns of behaviour of Batura and Hunza

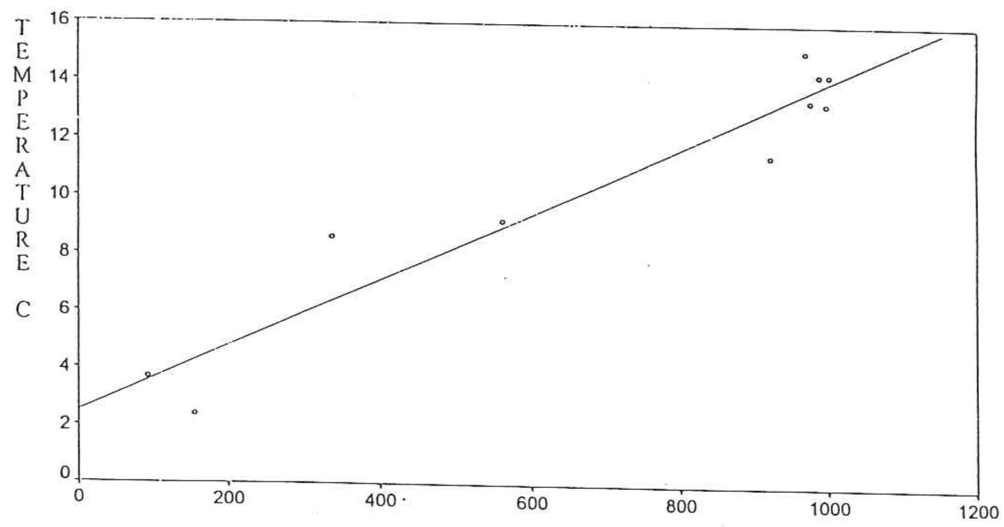


Figure 19. The relationship between daily average radiation and daily range of temperature at Passu terminus meteorological station in 1992.

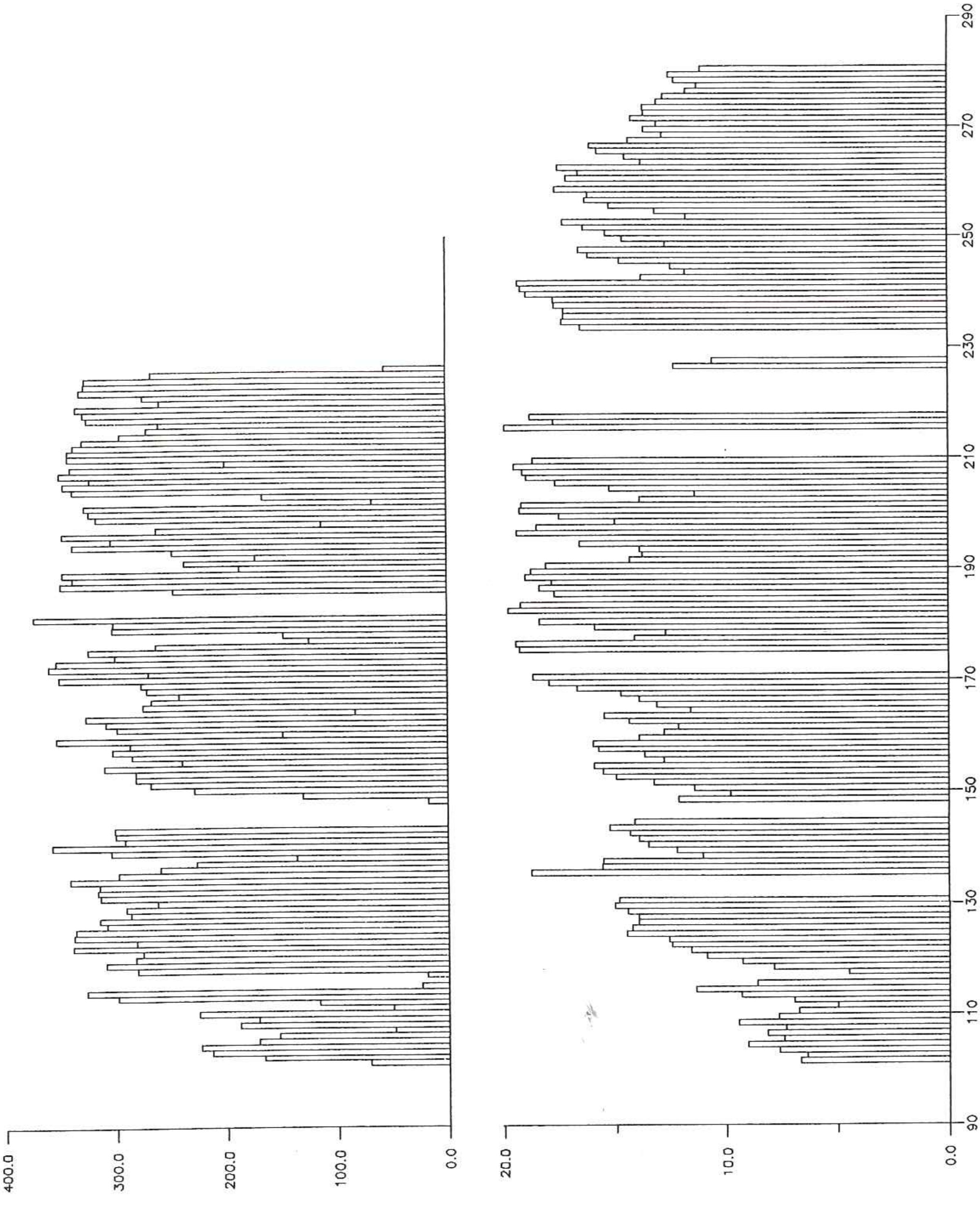


Figure 20. Relationship between air temperature (lower) and radiation (upper) recorded at Passu Glacier terminus meteorological station in the ablation season of 1990.

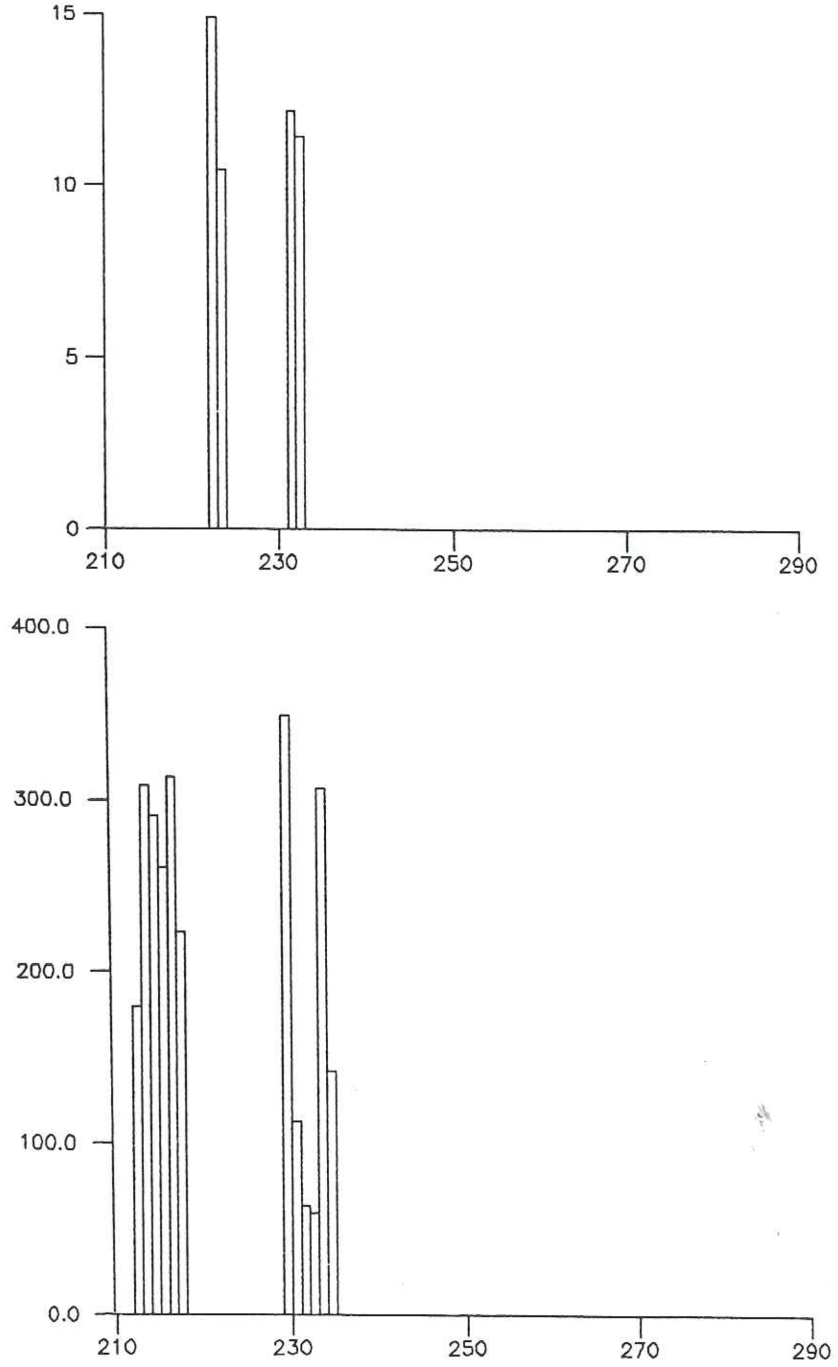


Figure 21. Relationship between radiation (lower) and precipitation (upper) recorded at Passu Glacier terminus meteorological station for a few days in the ablation season of 1992.

meltwaters should parallel each other. Similarly, the adjacent basins of Passu and Batura might be expected to behave in a similar way.

11.2 The Hunza at Dainyor Bridge

The Hunza at Dainyor Bridge is effectively the benchmark station for the glacierised areas of the Karakoram proper, that is excluding the more monsoonal areas around Nanga Parbat. The long term records of flow collected by WAPDA, available from 1966 - 1981, indicate the glacial source of the water. Flow starts to increase in May, and often with a snow melt peak first rises to a peak runoff in July and August (Figure 22).

Year-to-year variations of flow in the Hunza are greater than for similar variations of glacier-fed rivers in Europe (Collins 1985). and in North America, as indicated by coefficients of variation calculated for rivers of differing percentage glacierisation. The lower annual variability of runoff in glacier-fed rivers than in other basins without storage of ice usually arises from the compensation for shortage of runoff from liquid precipitation during dry weather being brought about by warm dry conditions favouring melt and the production of glacier meltwater. Conversely, in wet cool summers, reduced melt contributions to runoff are offset by runoff from rainfall. Proportions of the total basin area occupied by glaciers and free of ice influence the relative weighting of the rain and melt factors, as indeed must the precipitation and ablation gradients. In the Karakoram, the aridity of the valleys ensures that there is very little precipitation to generate runoff although snowfall in summer reduces meltwater production at high elevation. This topic requires further investigation in basins of varying proportions of glacierisation in the Karakoram.

The record of stage only of the Hunza at the WAPDA station at Dainyor Bridge is shown in Figure 23 for the period 20 July to 3 September 1989. The usual diurnal rhythm of flow is clear. Stage increased by 2m in late July, which corresponds to a period of exceptionally warm weather at high elevation from 25 July. This can be seen clearly as the group of high degree day totals at Patundas in Figure 18, in which it is also apparent that the degree day totals at the terminus of Passu Glacier form a fourth high energy-input period but no larger than the two previous events. At this time, radiation flux attained the highest level during the measurement period at Batura and Passu (Figure 12), which energy input must have caused the transient snowline to rise rapidly, greatly expanding the snow-free areas on the glacier surfaces, and allowing much ice to melt.

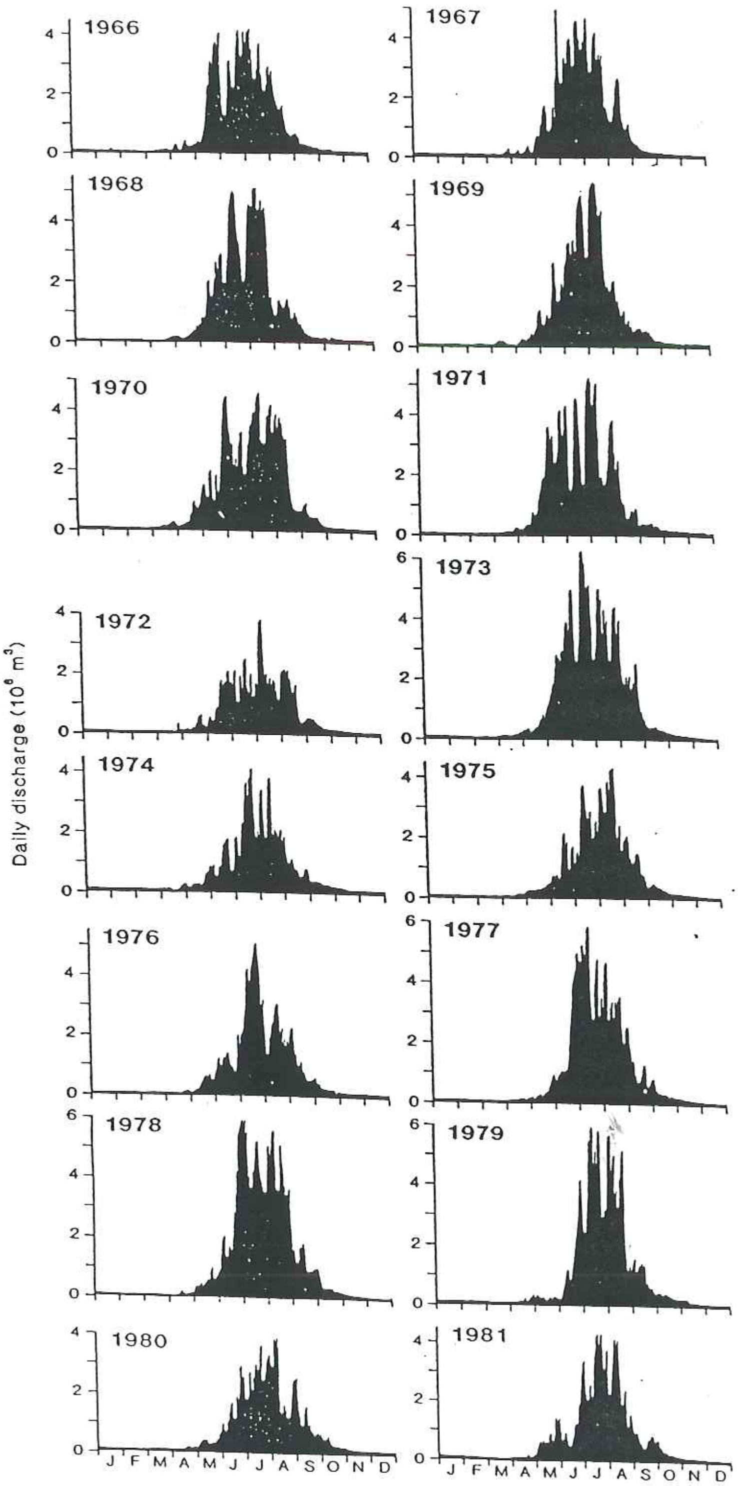


Figure 22. Daily total discharge of the Hunza River at Dainyor Bridge for the years 1966 - 1981.

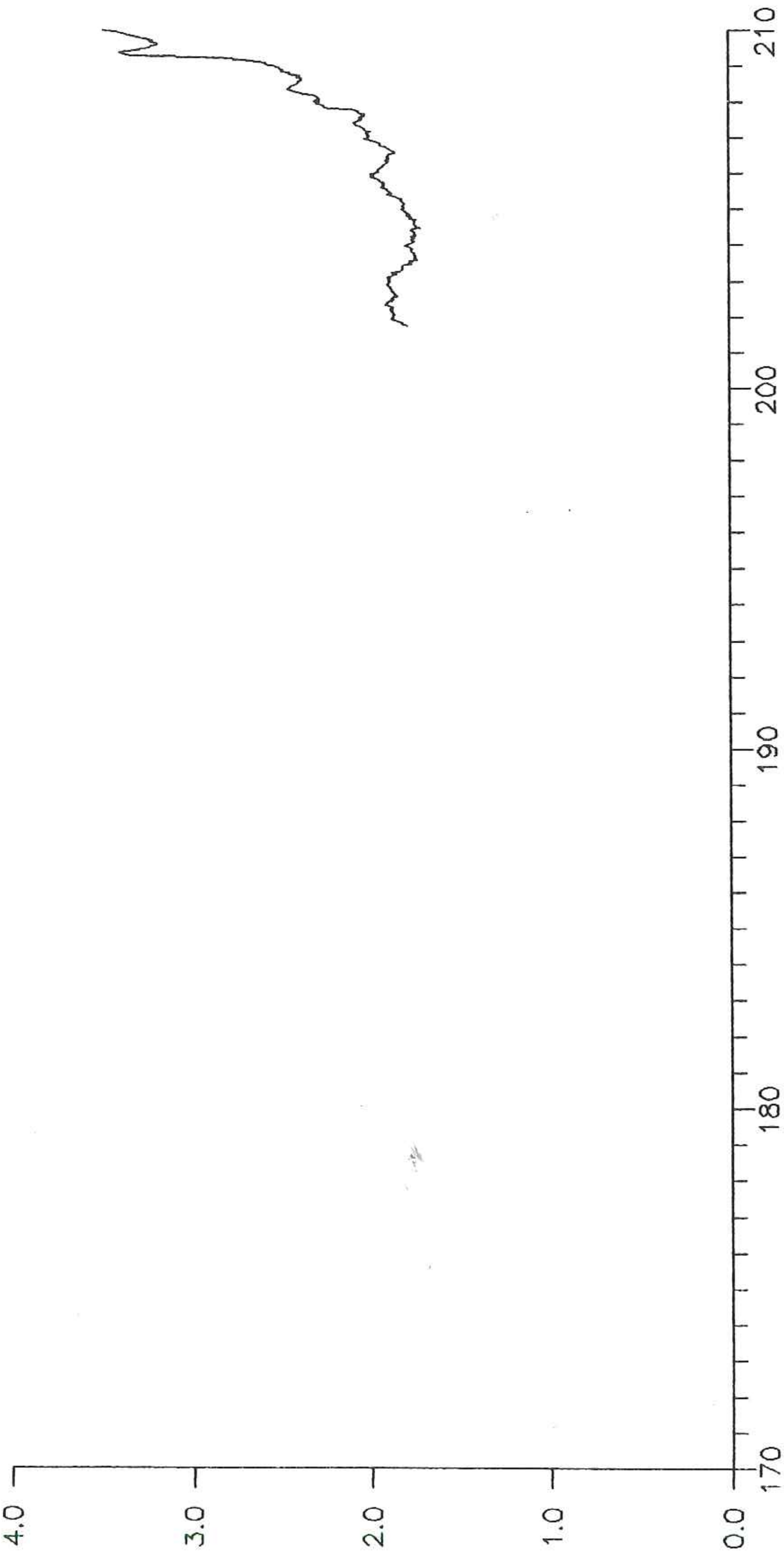


Figure 23. Stage of the Hunza at Dainyor Bridge in 1989.

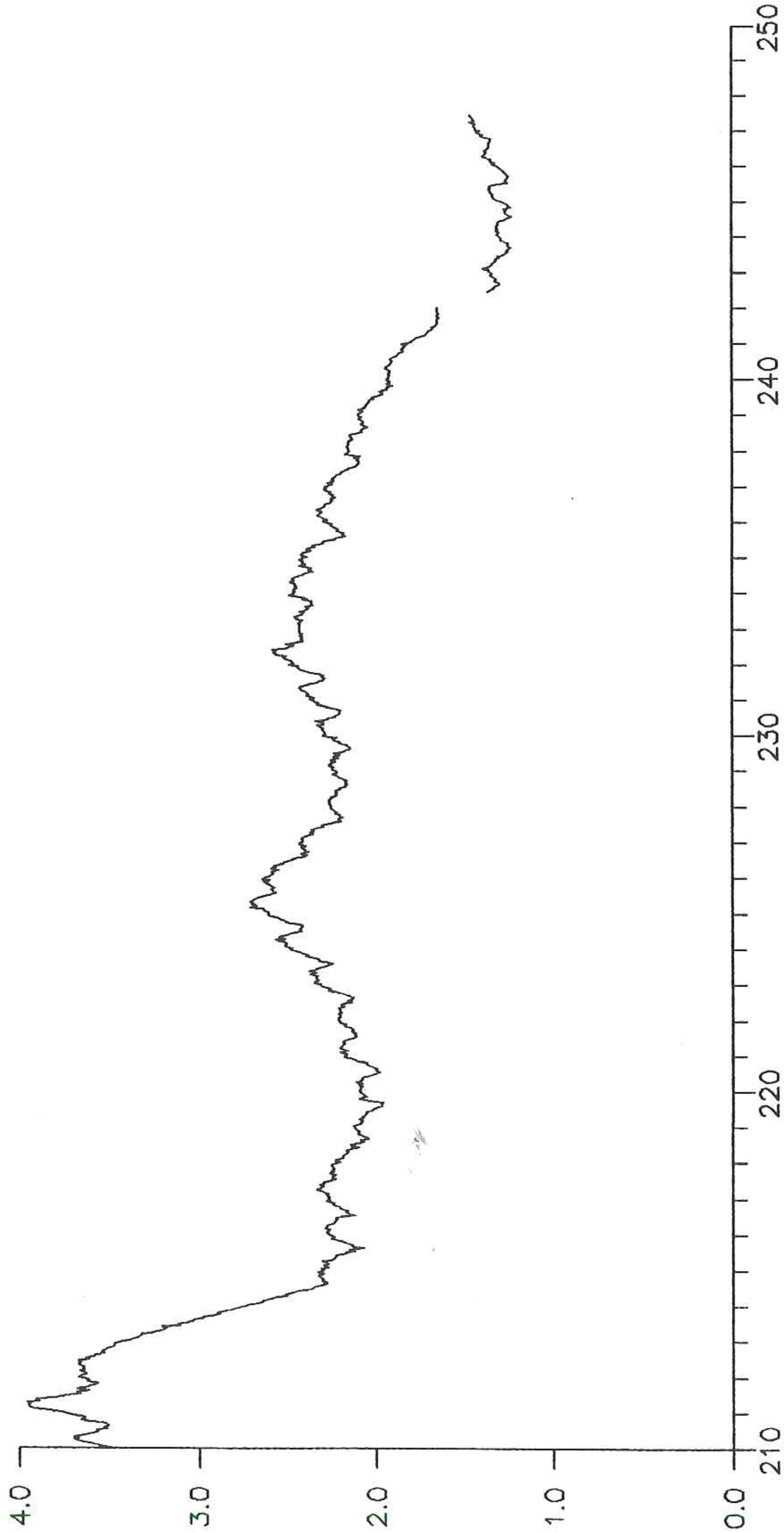


Figure 23 (continued). Stage of the Hunza at Dainyor Bridge in 1989.

11.3 Discharge from Batura and Passu glaciers in 1989

The longest, most continuous record of discharge obtained in 1989 was at Passu Bridge between 19 May and 17 October, encompassing most of the ablation season. However, by 19 May, discharge had already risen to 8 $m^3 s^{-1}$ by mid-May, and an important part of the spring melt had already occurred. The hydrograph consists of the usual diurnal rhythm of flow, occasionally superimposed on generally higher levels of background flow during periods of higher energy inputs (Figure 24). The daily peaks of flow are asymmetrical, but account for a maximum of 20 per cent of the flow in a 24 hour period. The 'background' may have remained so high on account of the warm nights and continuing glacier surface fusion of ice. There was little interruption to the diurnal rhythm of flow except when snowfall in the upper zone of the basin induced recession in late September and in October.

Continuous records of discharge at Batura Bridge in 1989 were broken by instrument malfunction. In the three periods of continuous flow monitoring diurnal asymmetric peaks are superimposed again on the general fluctuation of background flow (Figure 25). The basin is large, the elevation range great and the discharge exceptionally high, but the areas under the peaks of the diurnal hydrographs small by comparison with Passu. On first sight, this would suggest that the gauging on which the rating curve was based might be at fault, and indeed the high velocities, turbulence and standing waves of the Batura river made velocity measurements impossible at flows above about 100 $m^3 s^{-1}$. However, in terms of specific discharge, the absolute quantities of meltwater gauged at Passu and Batura appear reasonable. On comparable days, total flow from Batura is about 5 times that from Passu glacier. The ratio of size, both basins being similarly glacierised, is 5.85.

Figure 26 shows the daily total discharge from Batura and Passu glaciers in 1989. Where the curves can be compared, it is apparent that the discharge from Batura Glacier responds more slowly to a period of warmer weather than Passu. Similarly, after such periods recession at Batura can be slower, particularly at the start of the season.

11.4 Stage of the Braldu at Dassu in 1989

The stage curve recorded for the Braldu at Dassu has some similarity with the hydrograph at Passu, in parallel during two periods of enhanced flow (compare Figures 26 and 27). Unfortunately, there is inadequate overlap in the stage record at Dassu with that at Dainyore to allow comment on the wider general regional trend in climatic and

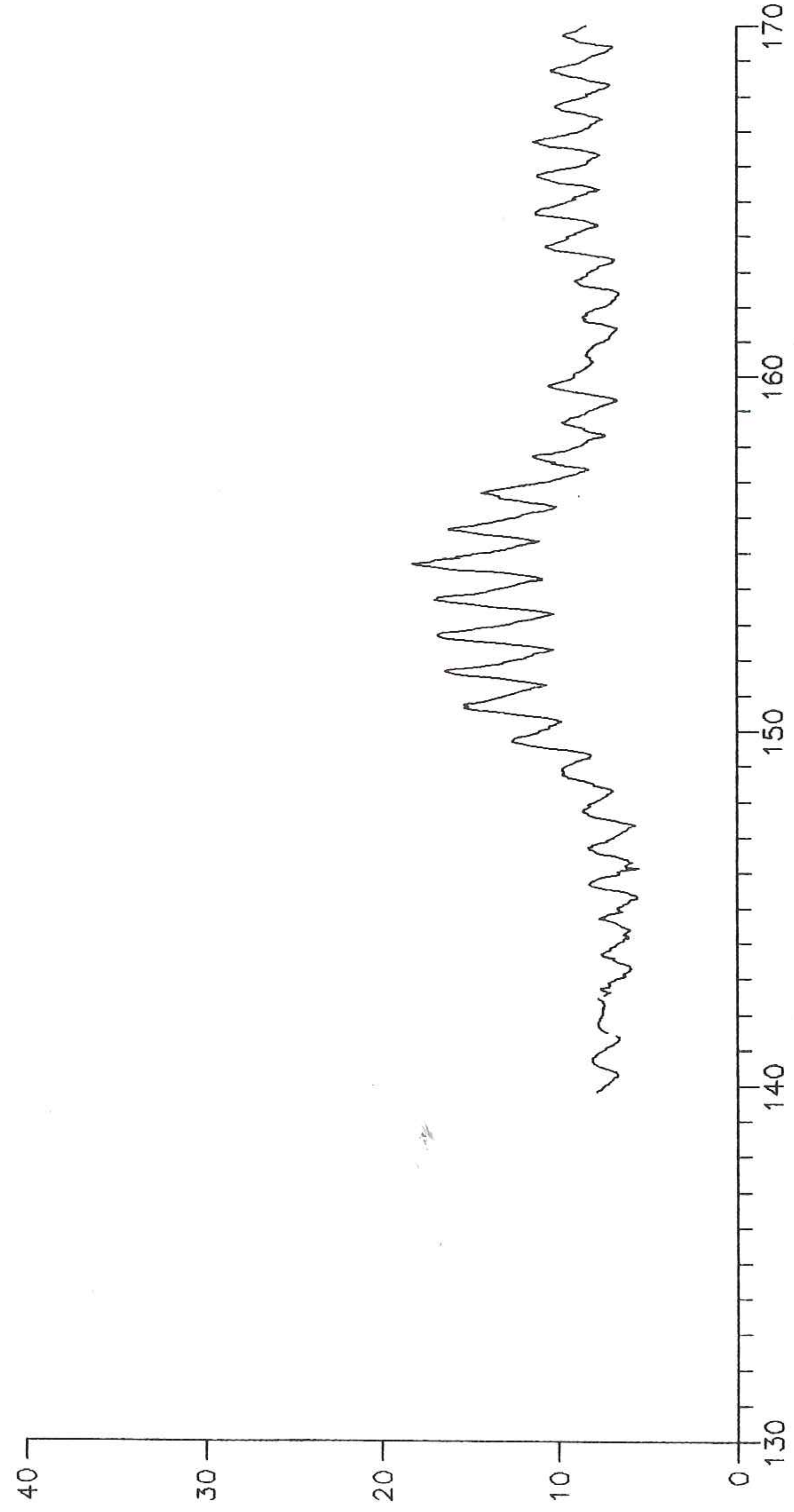


Figure 24. Discharge from Passu Glacier in the ablation season of 1989.

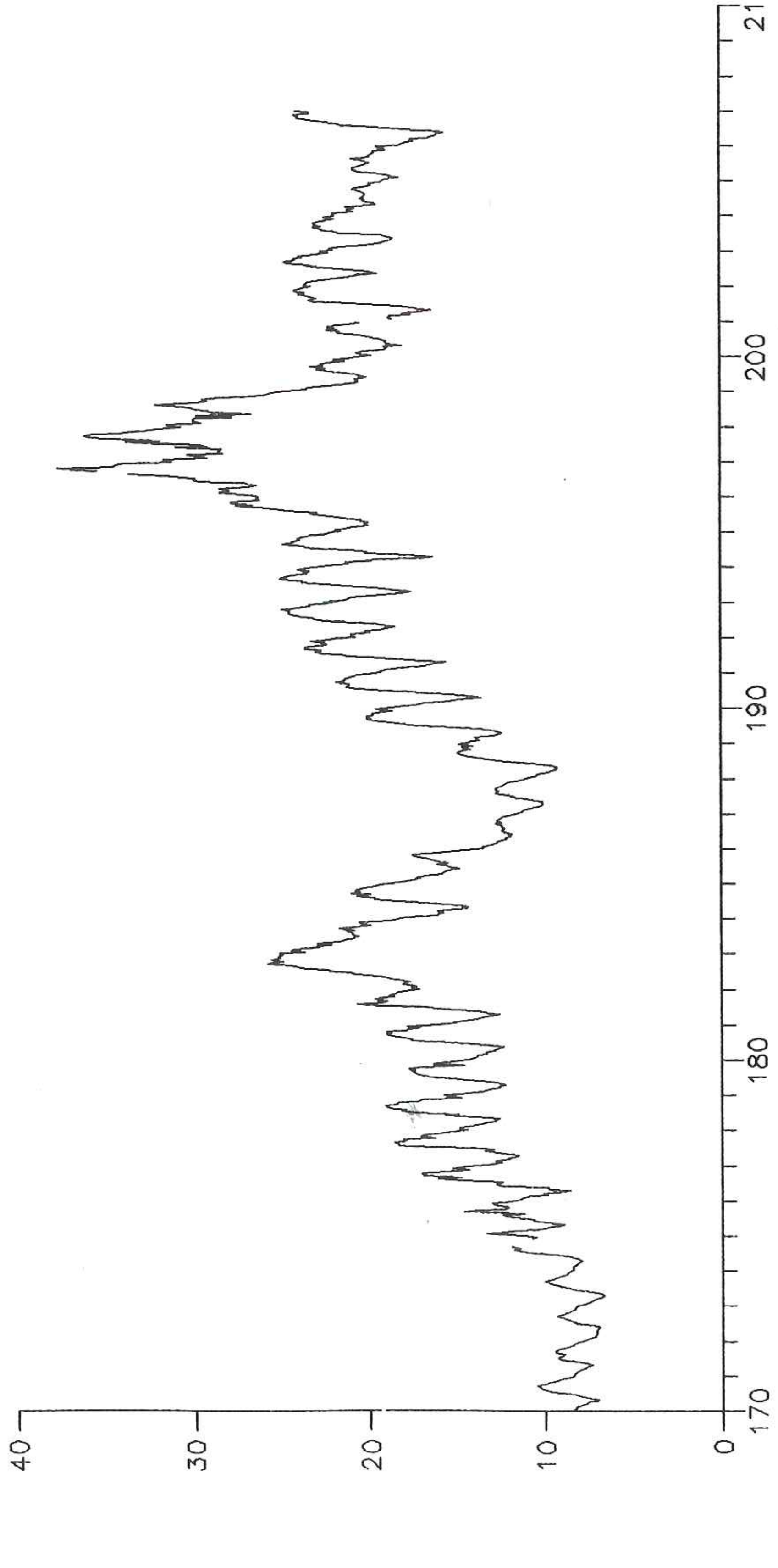


Figure 24 (continued). Discharge from Passu Glacier in the ablation season of 1989.

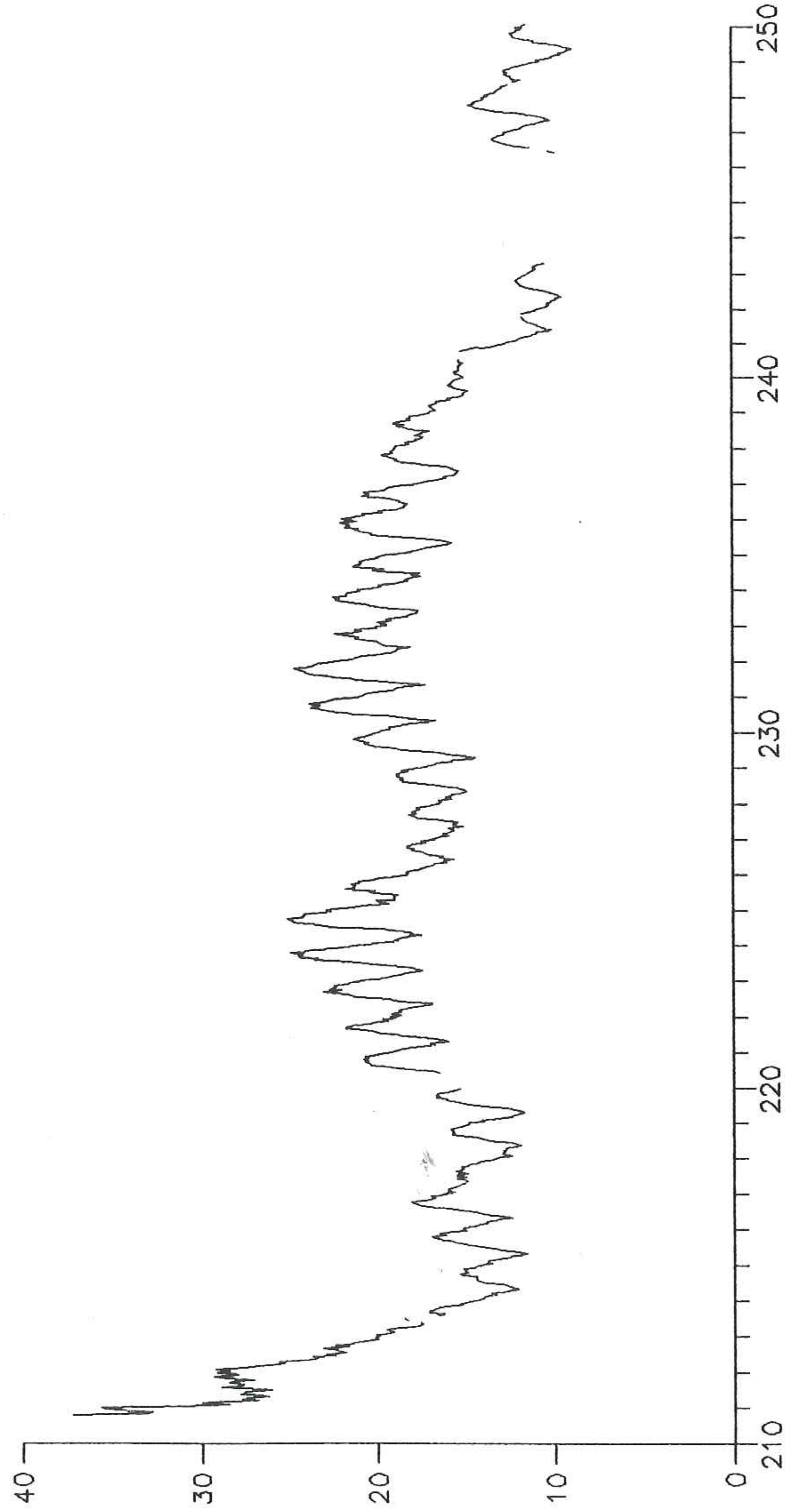


Figure 24 (continued). Discharge from Passu Glacier in the ablation season of 1989.

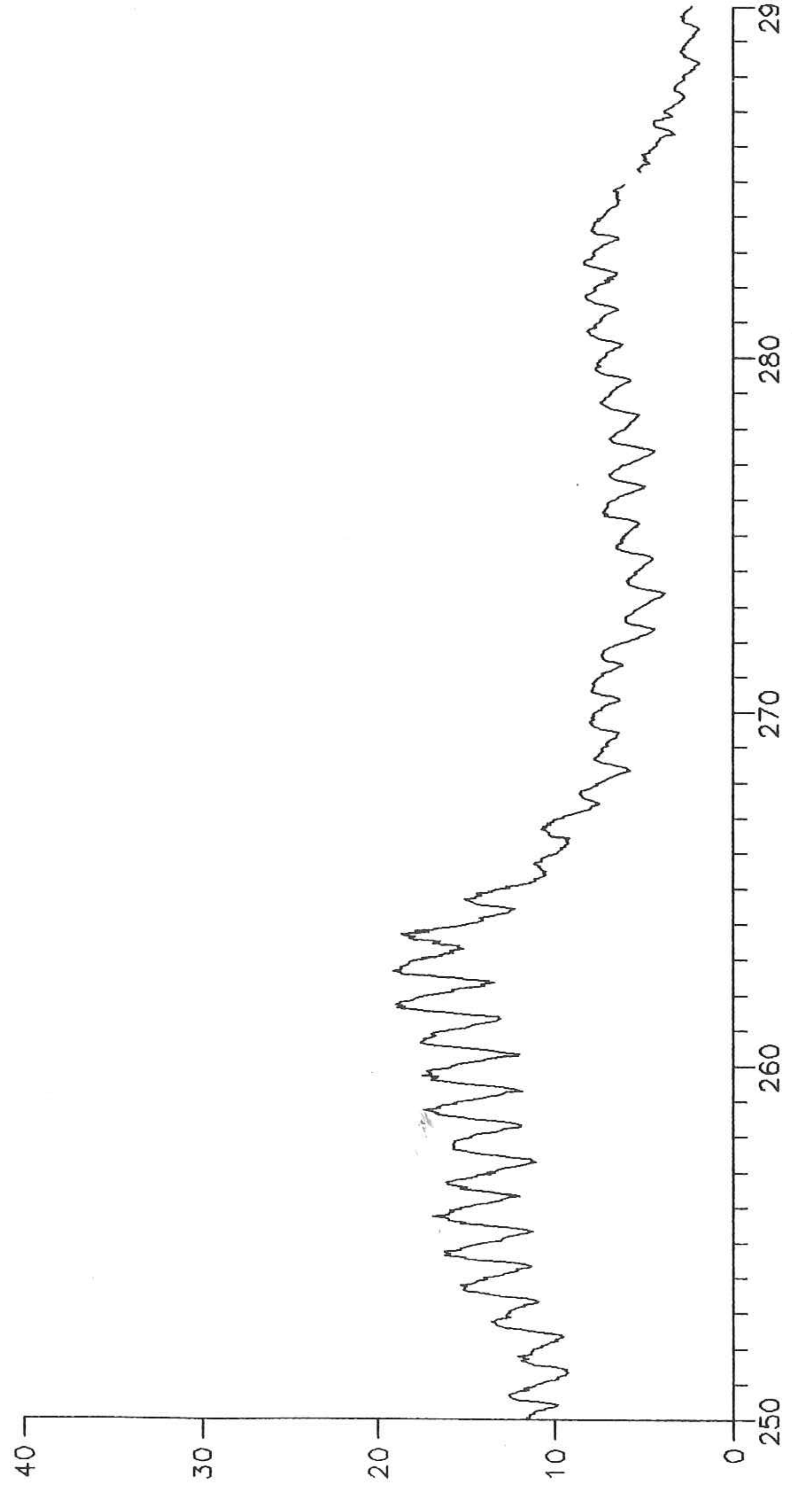


Figure 24 (continued). Discharge from Passu Glacier in the ablation season of 1989.

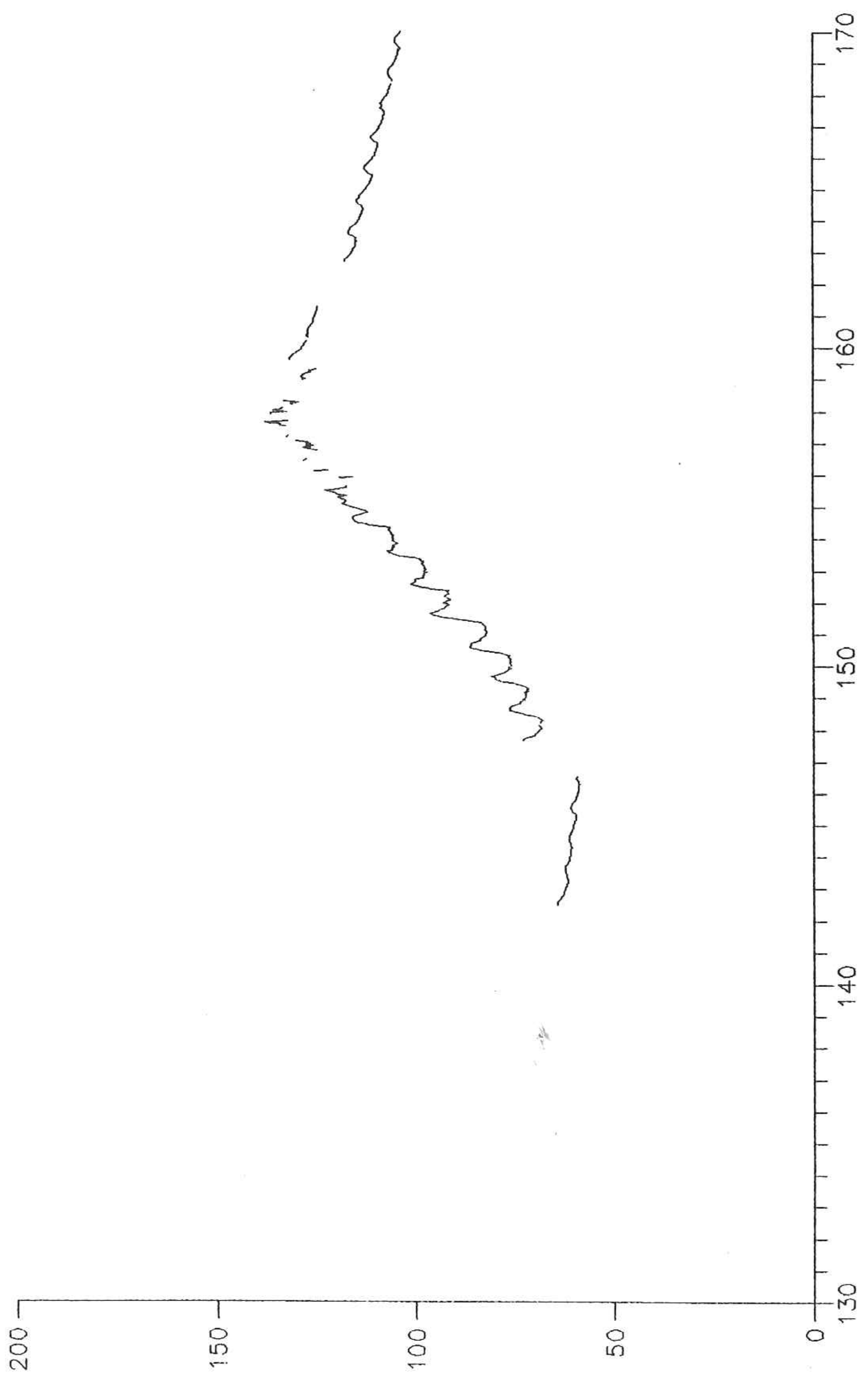


Figure 25. Discharge ($m^3 s^{-1}$) from Batura Glacier in the ablation season of 1989.

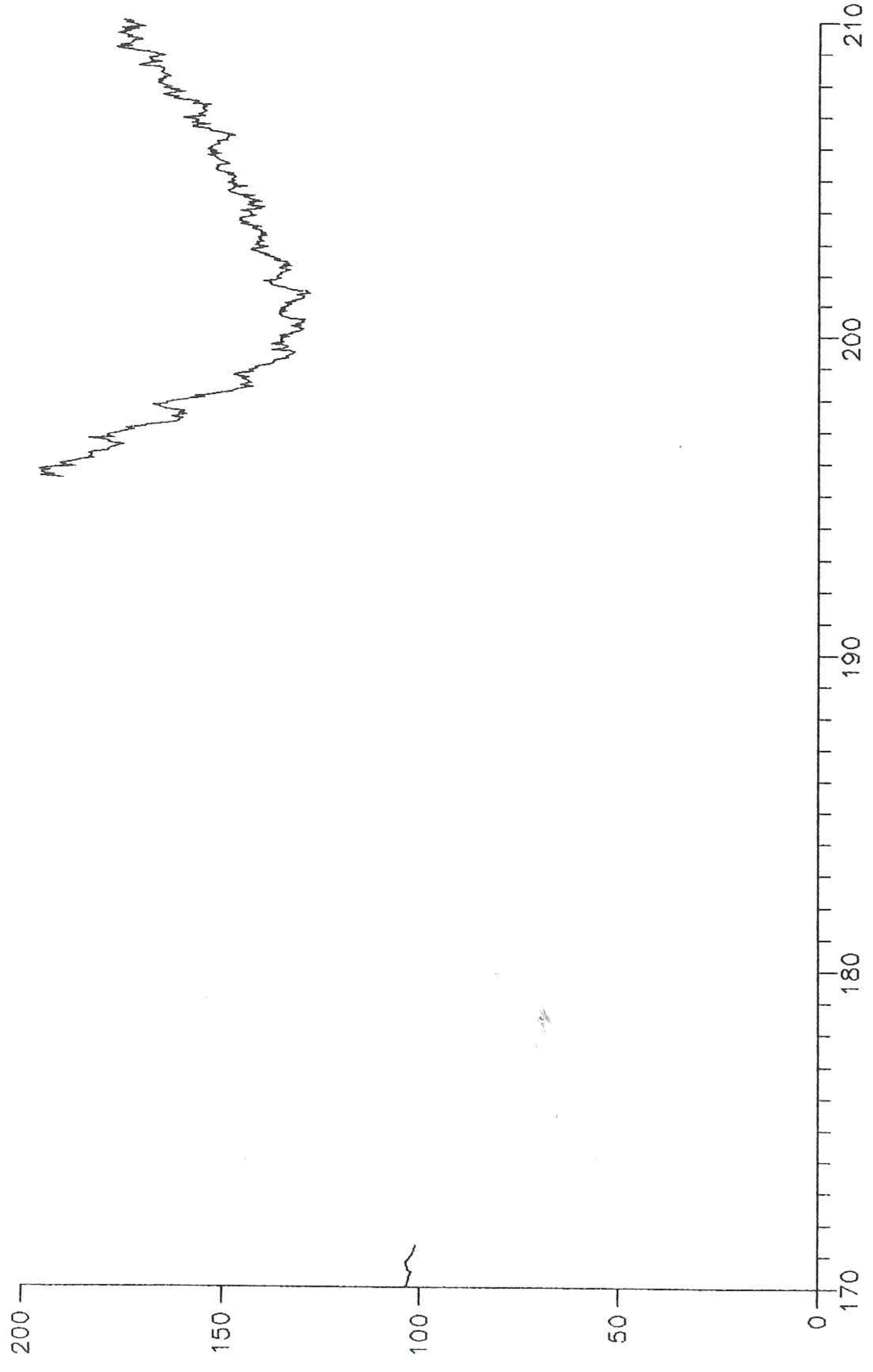


Figure 25 (continued). Discharge ($m^3\ s^{-1}$) from Batura Glacier in the ablation season of 1989.

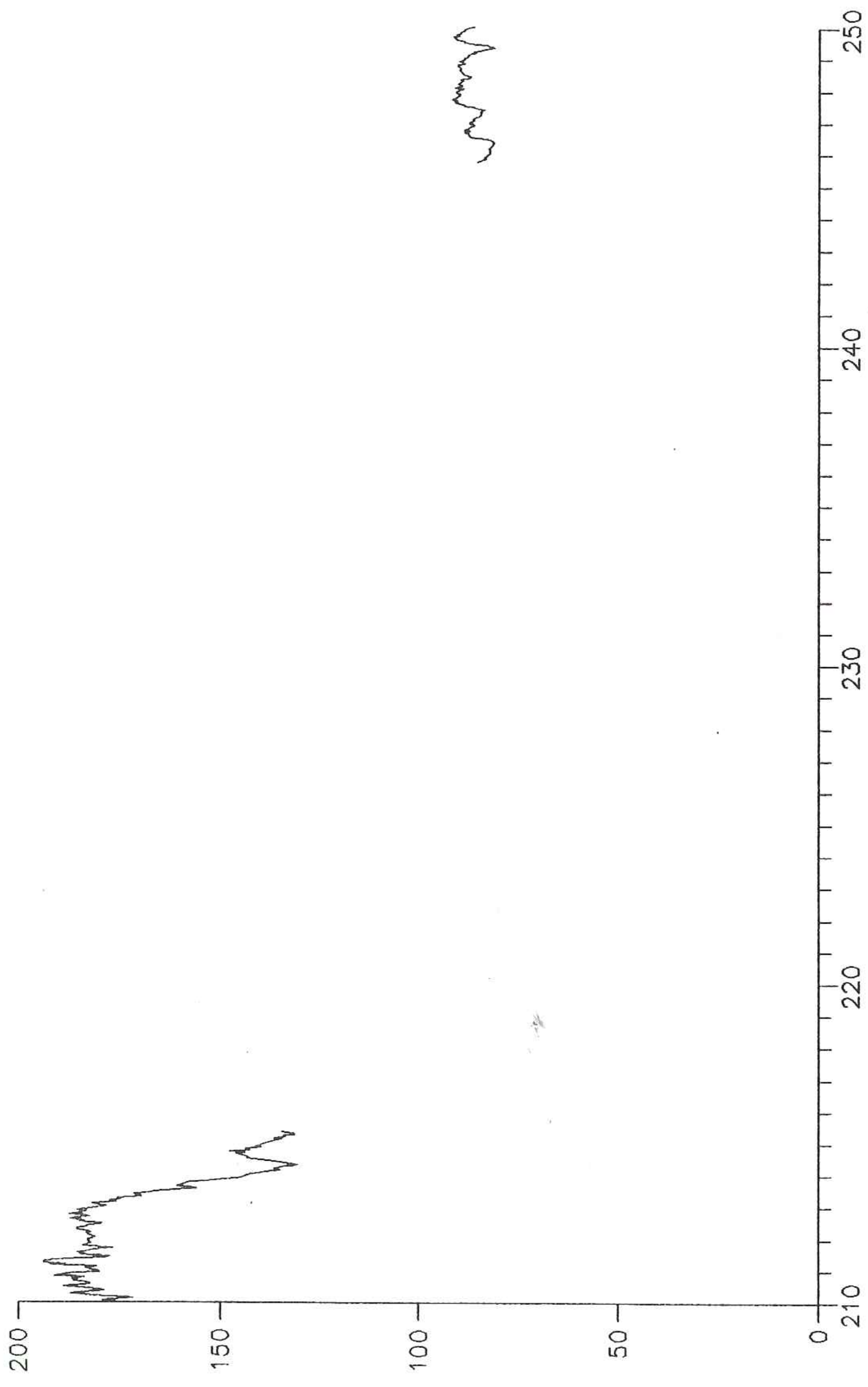


Figure 25 (continued). Discharge (m^3 s^{-1}) from Batura Glacier in the ablation season of 1989.

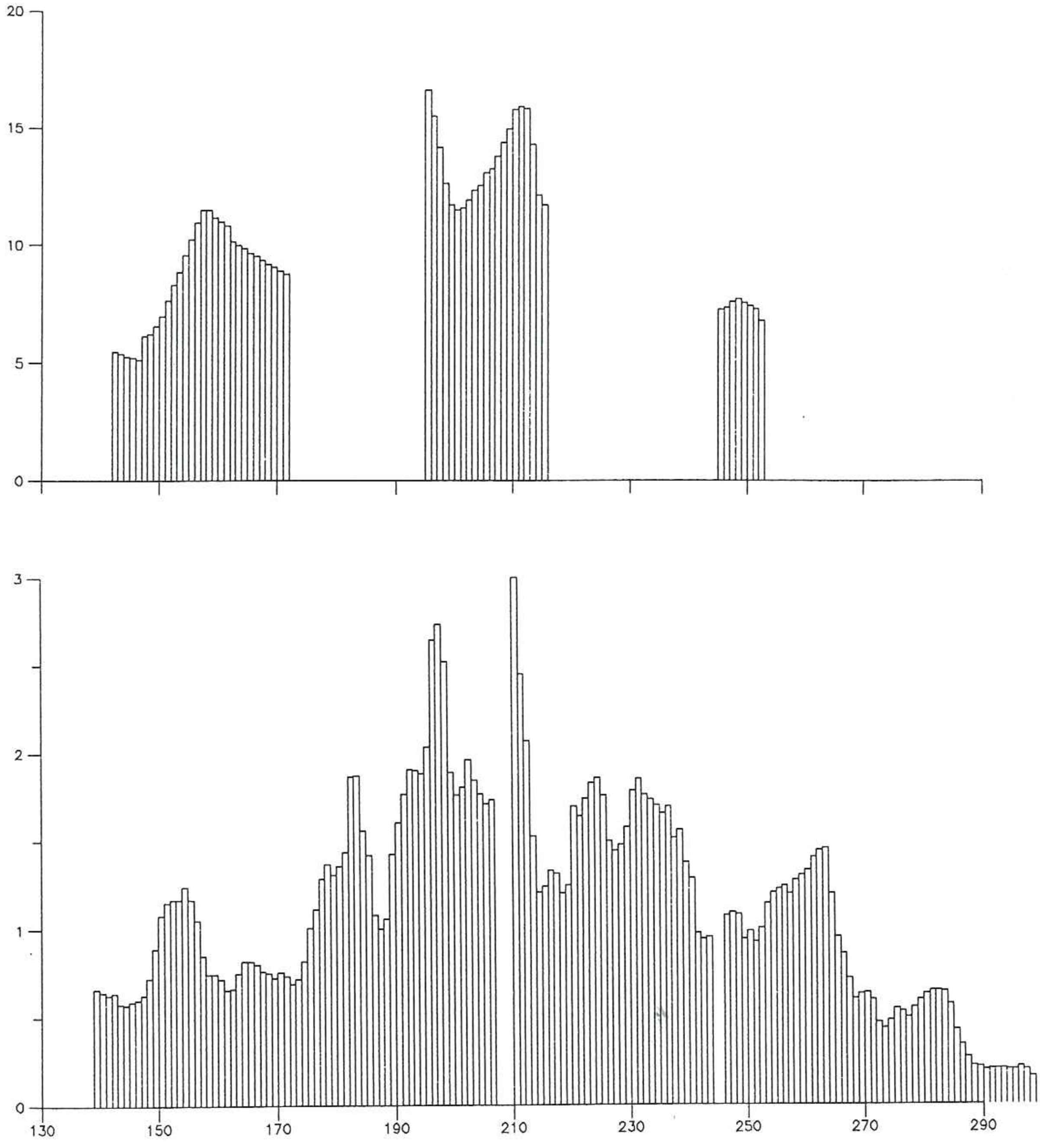


Figure 26. Discharge ($m^3\ s^{-1}$) from Batura Glacier (upper) and Batura Glacier (lower) in the ablation season of 1989.

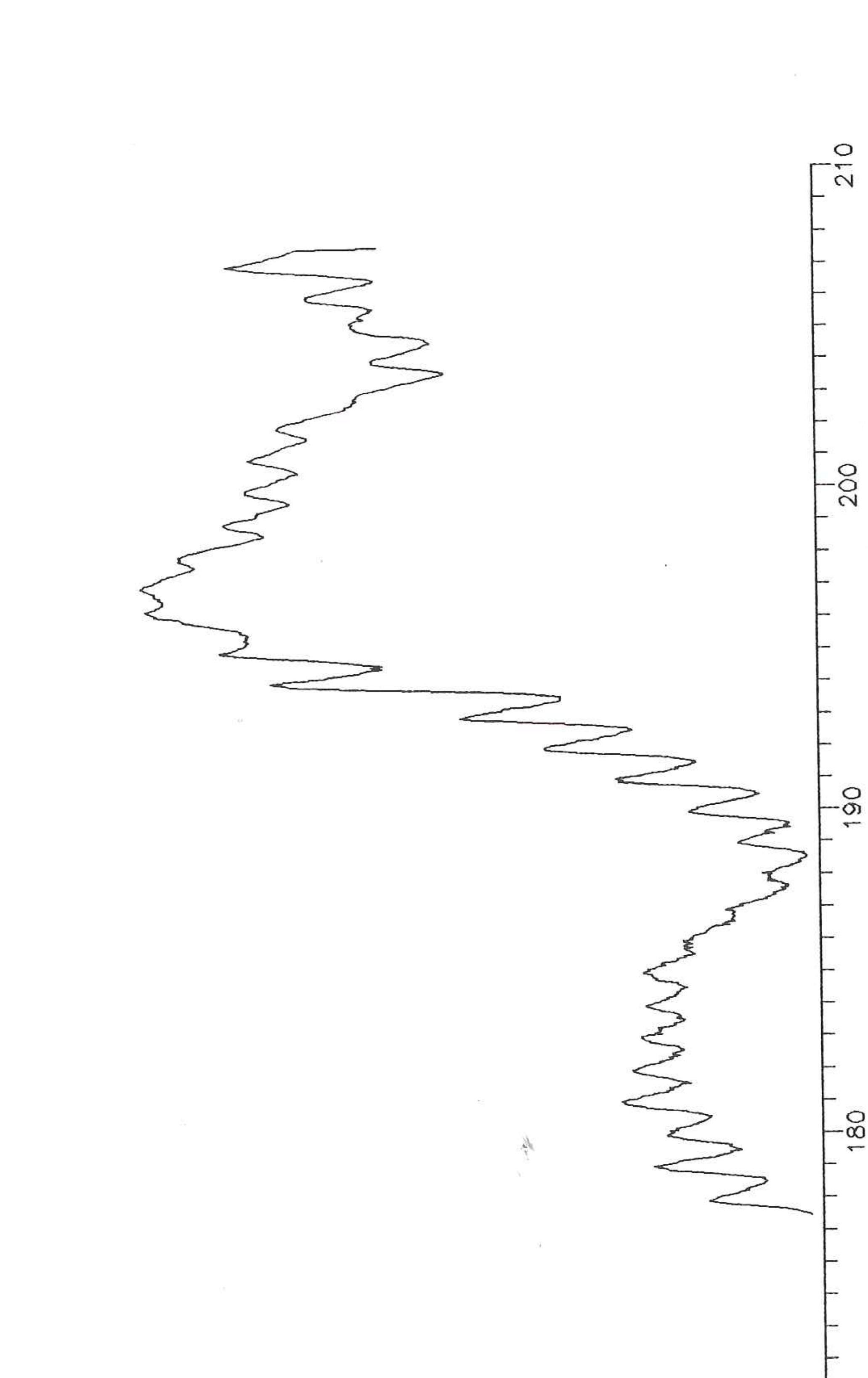


Figure 27. Stage (m) of the Braldu at Dassu Bridge in 1989.

glacier runoff characteristics.

11.5 Discharge from Batura and Passu glaciers in 1990

Continuous records of discharge were obtained from both basins from April to mid-October in 1990 (Figures 28 and 29). In general, the temporal pattern of variation is parallel in these series, representing a response to the same episodes of warmer and cooler weather in the sequence.

Several periods differ in quantity, if not in pattern. At the beginning of August, the flow from Batura is consistently higher than from Passu glacier. This may reflect later expansion of the ice-free area to higher elevation at Batura. Conversely, there are three episodes in the early part of the season in which runoff from Passu is considerably higher for the period than discharge from Batura. These episodes occurred between 12 - 17 May, 5 - 13 June and 24 -27 June. Hourly plots of discharge show the detail of these anomalies (Figure 30). They cannot be explained by short-term energy increases as the air temperature record at Passu Glacier terminus indicates (Figure 31). The probable explanation is that large pockets of water, temporarily stored beneath Passu glacier have been released, not suddenly with an increasing monotonic hydrograph as would be the case of the draining of a marginal ice-dammed lake. Unfortunately, continuous water quality monitoring had been discontinued as a result of the nature of the observations made in 1989 (see below).

A final runoff anomaly in February 1991 was so large as to wash away the gauging station. Sudden large discharges of water from mountain glaciers are probably less common in winter than in summer although ice-dammmed lakes can drain at any time.

11.6 Discharge from Batura glaciers in 1991 and 1992

By May 1991, only the station at Batura remained intact. Discharge was recorded between May and September 1991 (Figure 32). The season in 1992 was less successful than the previous three. The stage board at Batura disappeared during winter, and a new site had to be chosen. A stable stage-discharge relationship for this board proved elusive. The final tailfin became detached from a Braystoke current meter rendering the system unusable. The final straw was the flood of early September. It should be recalled that the investigations by Lanzhow Institute (1980) were commenced as a result of the change of position in 1974 of the Batura river channel, sudden migration of which destroyed the concrete bridge of and closed to traffic the then newly-constructed Karakoram Highway.

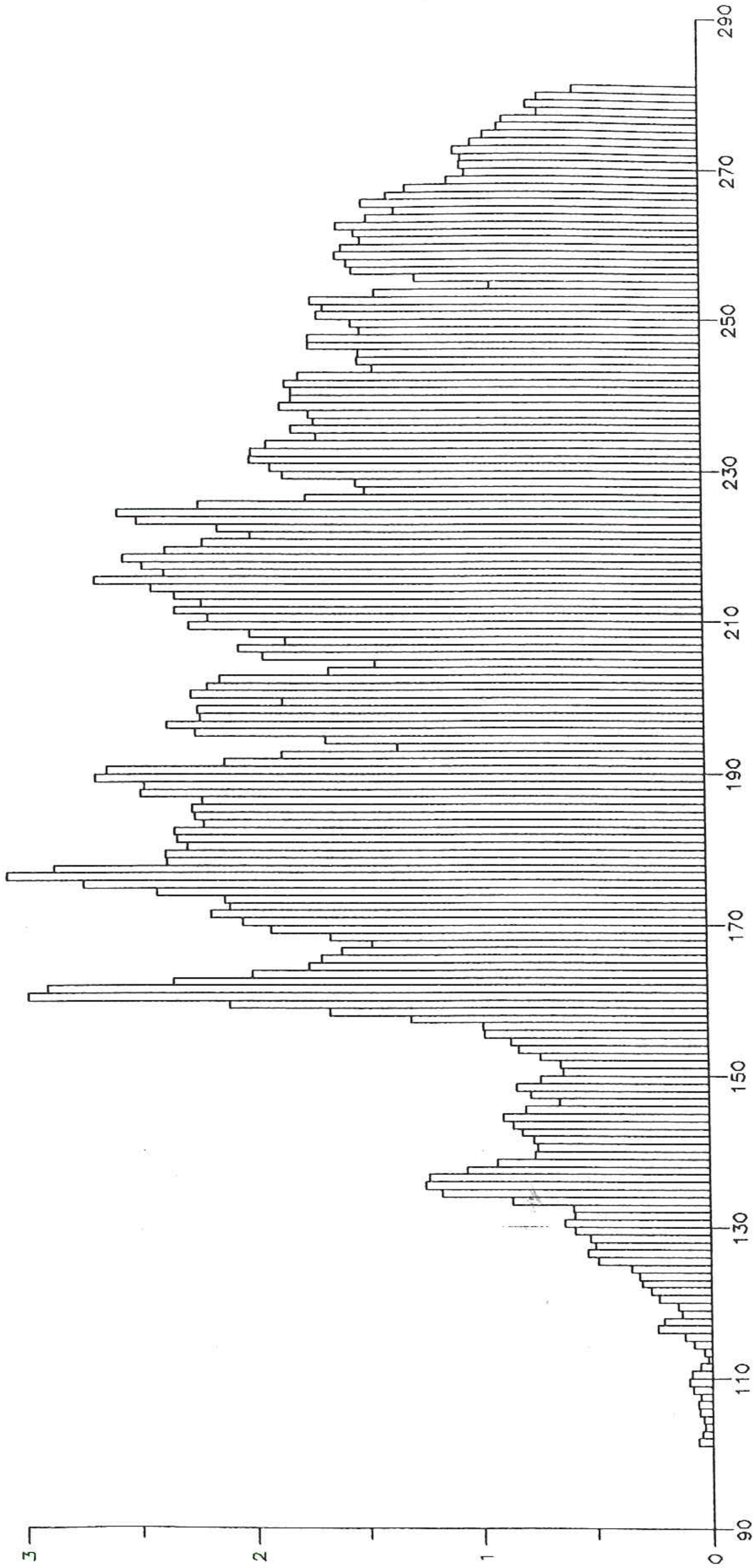


Figure 28. Daily total discharge ($x10^6$) from Passu Glacier in the ablation season of 1990.

Figure 29. Daily total discharge ($x10^6$) from Batura Glacier in the ablation season of 1990.

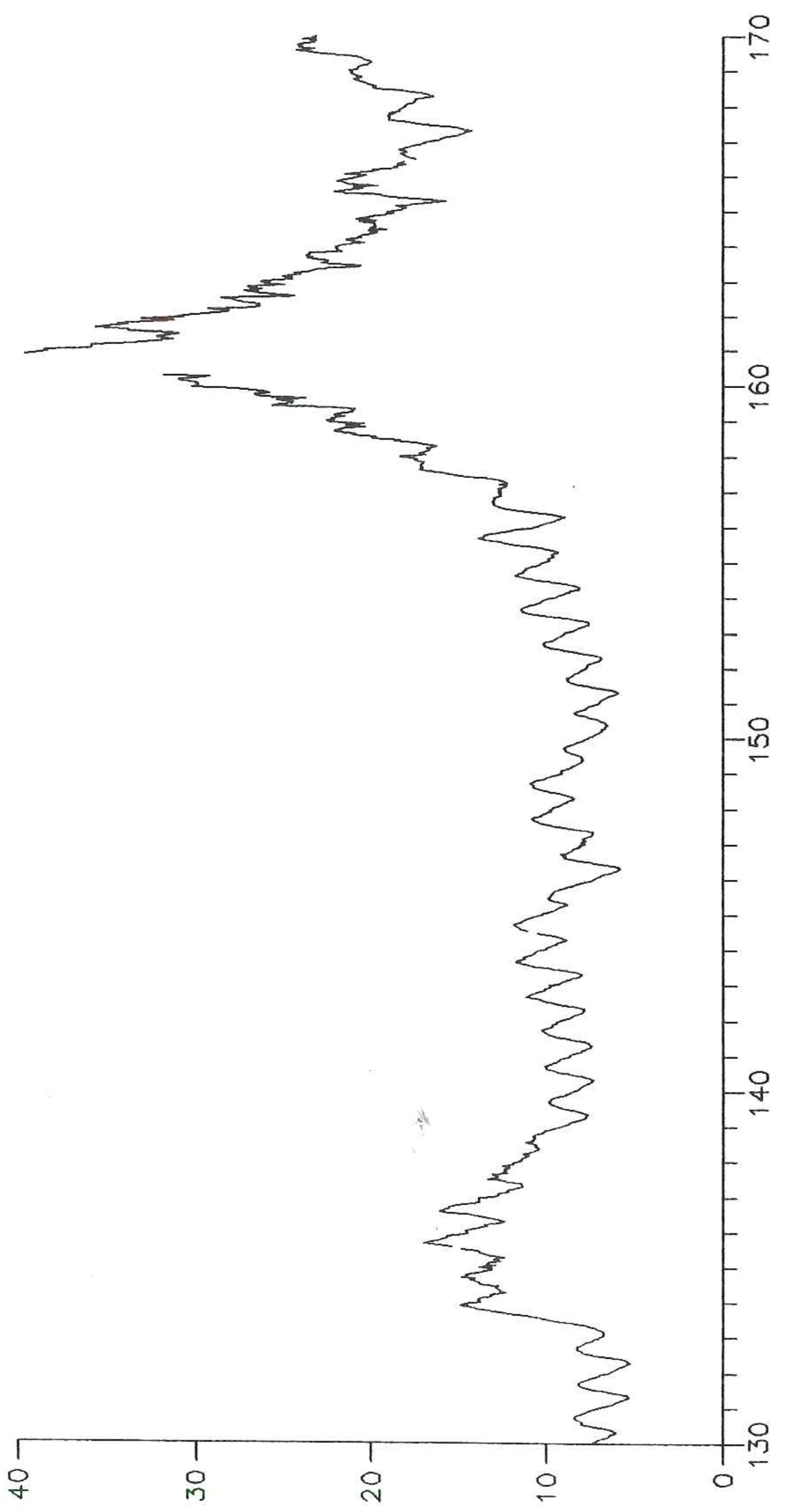


Figure 30. Discharge ($m^3\ s^{-1}$) from Passu Glacier in the ablation season of 1990.

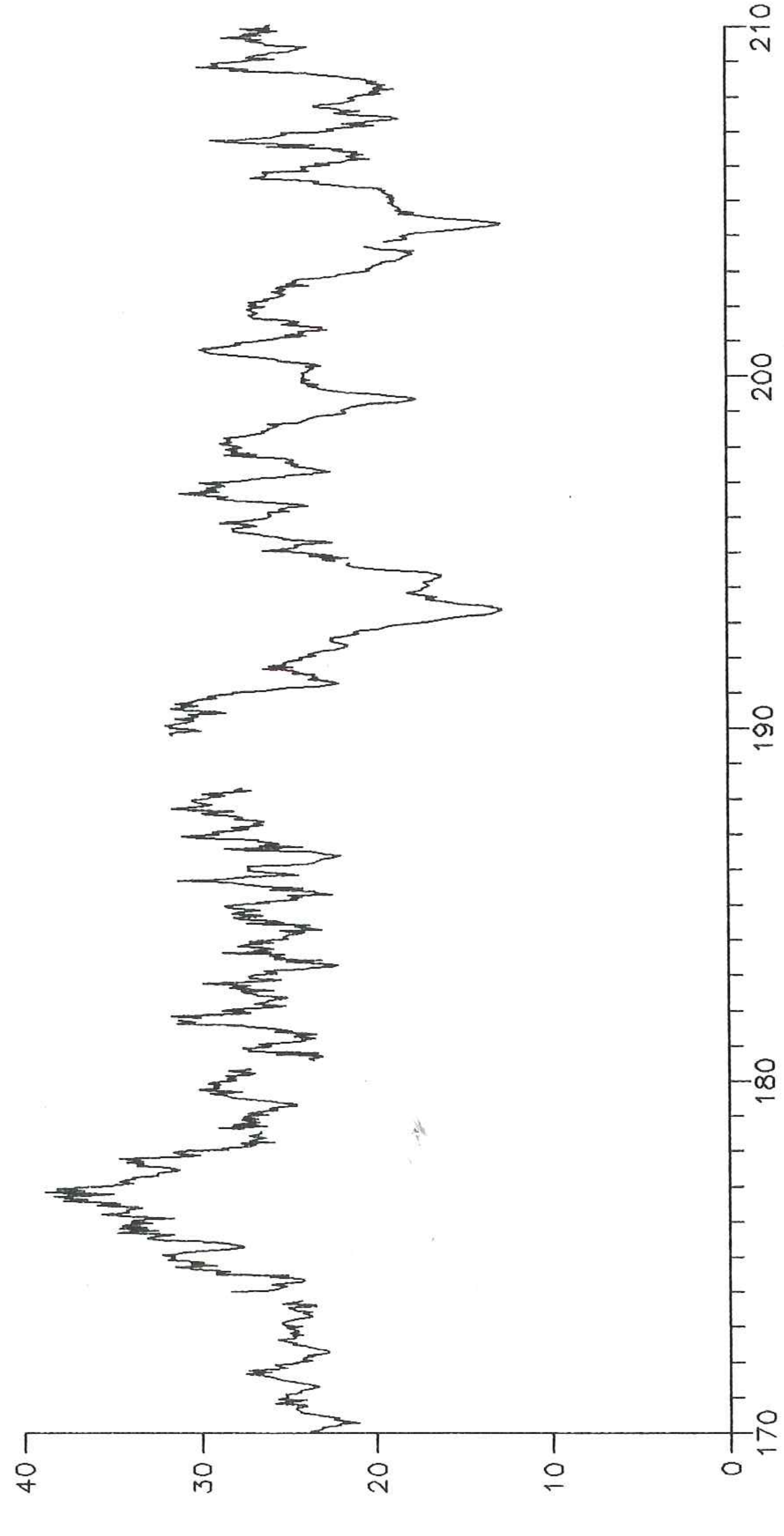


Figure 30 (continued). Discharge ($m^3\ s^{-1}$) from Passu Glacier in the ablation season of 1990.

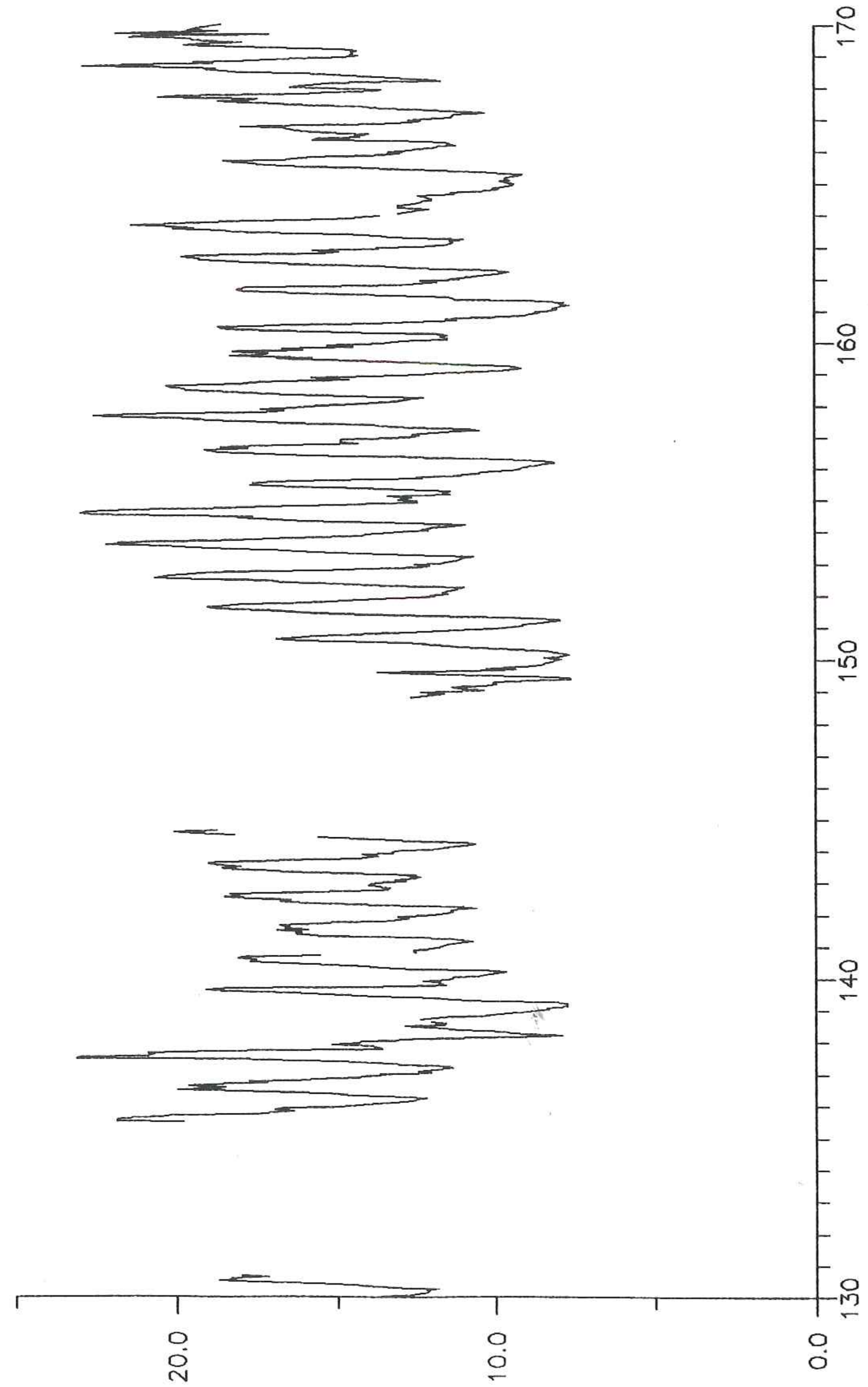


Figure 31. Air temperature (^{0} Celsius) at Passu Glacier meteorological station in the ablation season of 1990.

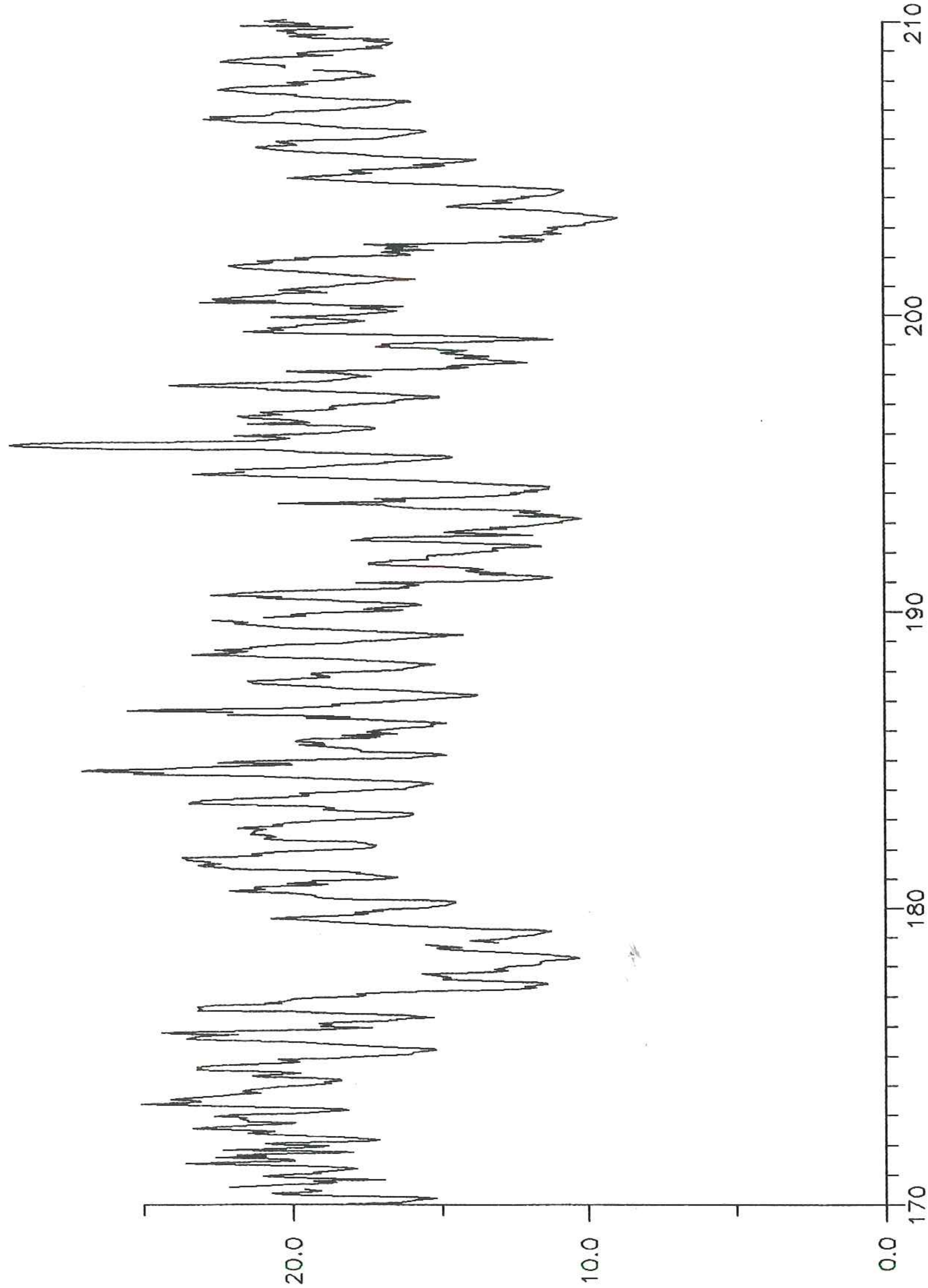


Figure 31 (continued). Air temperature (^{0} Celsius) at Passu Glacier meteorological station in the ablation season of 1990.

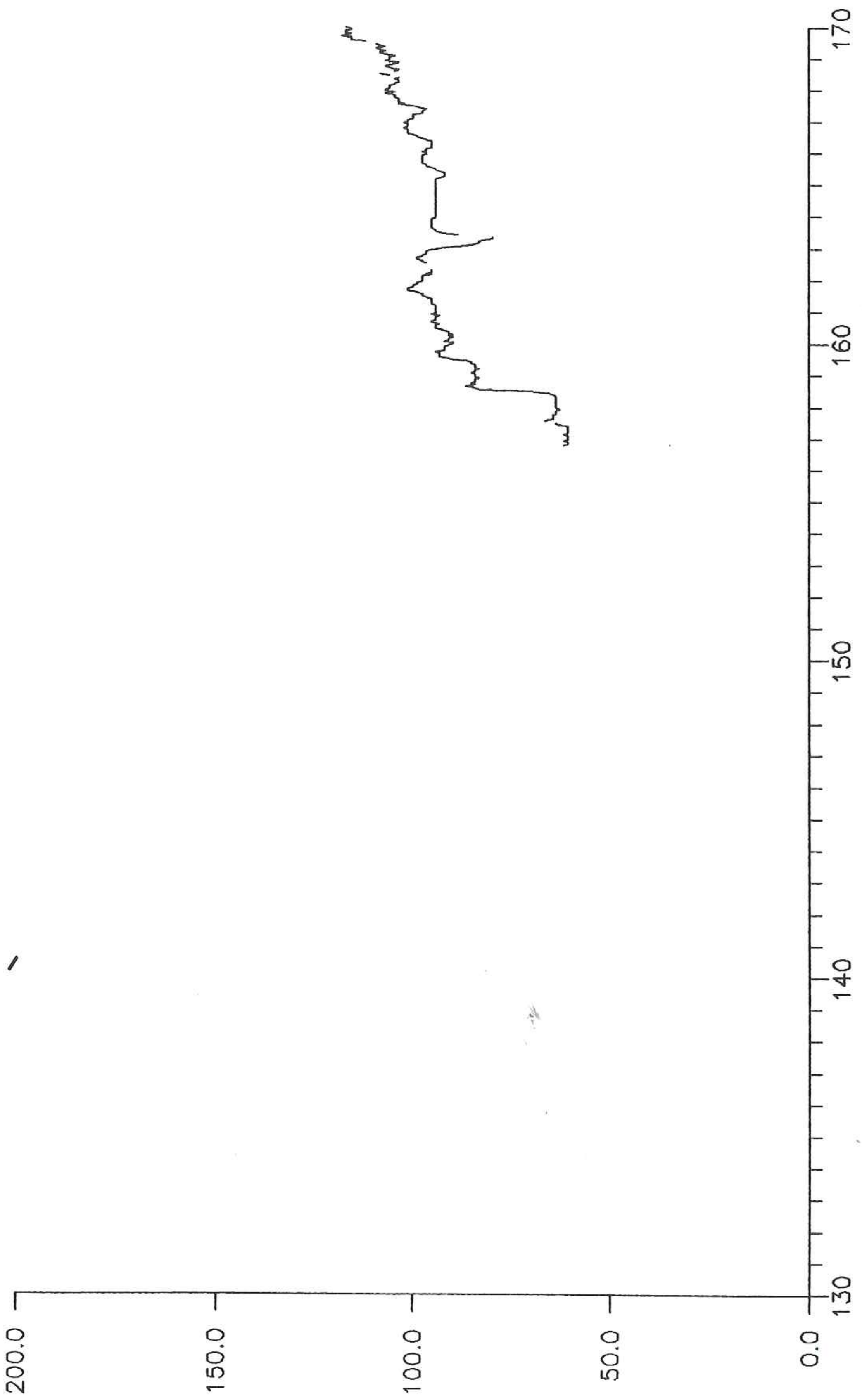


Figure 32. Discharge (m^3 s^{-1}) from Batura Glacier in the ablation season of 1991.

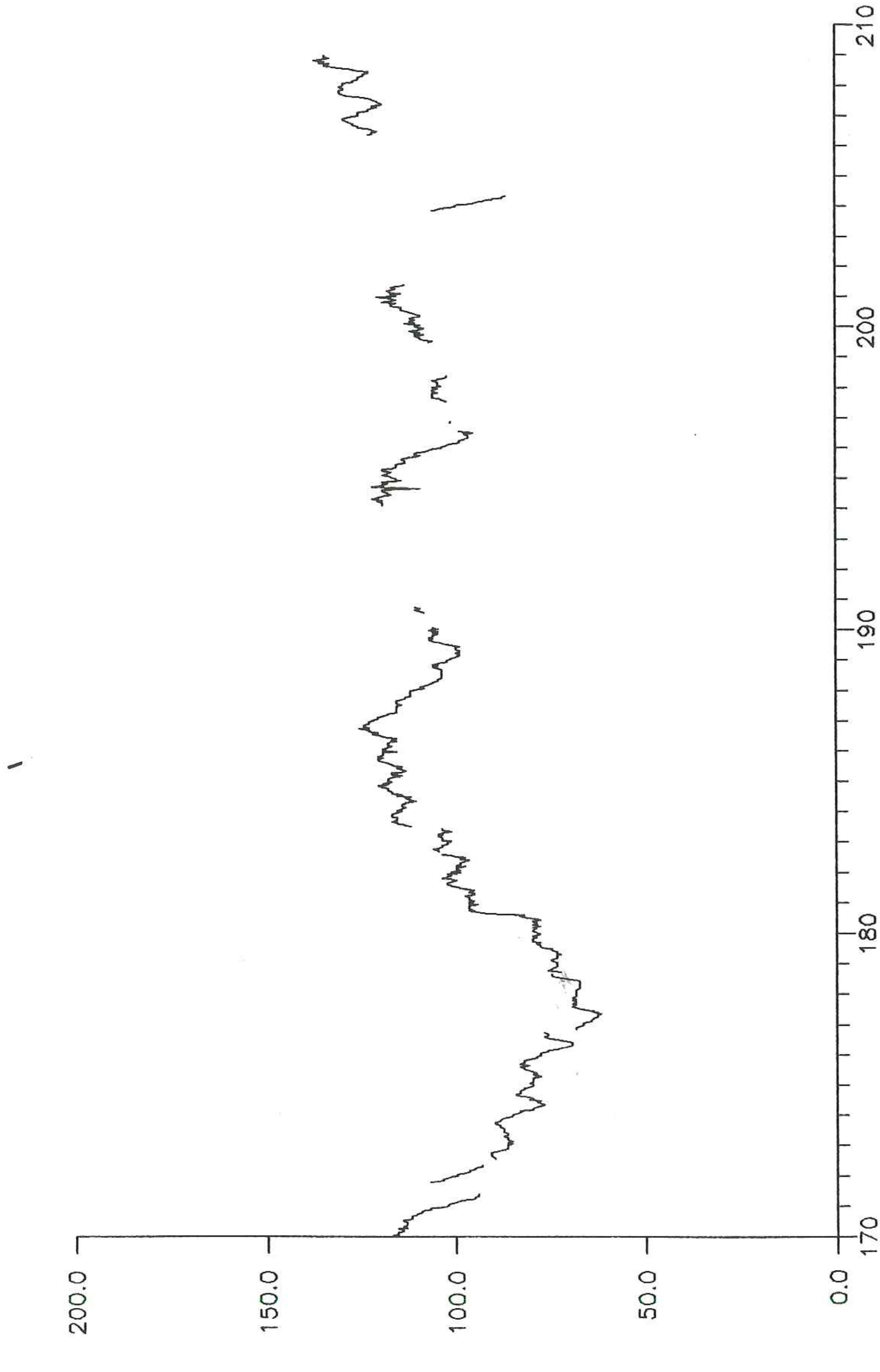


Figure 32 (continued). Discharge (m^3 s^{-1}) from Batura Glacier in the ablation season of 1991.

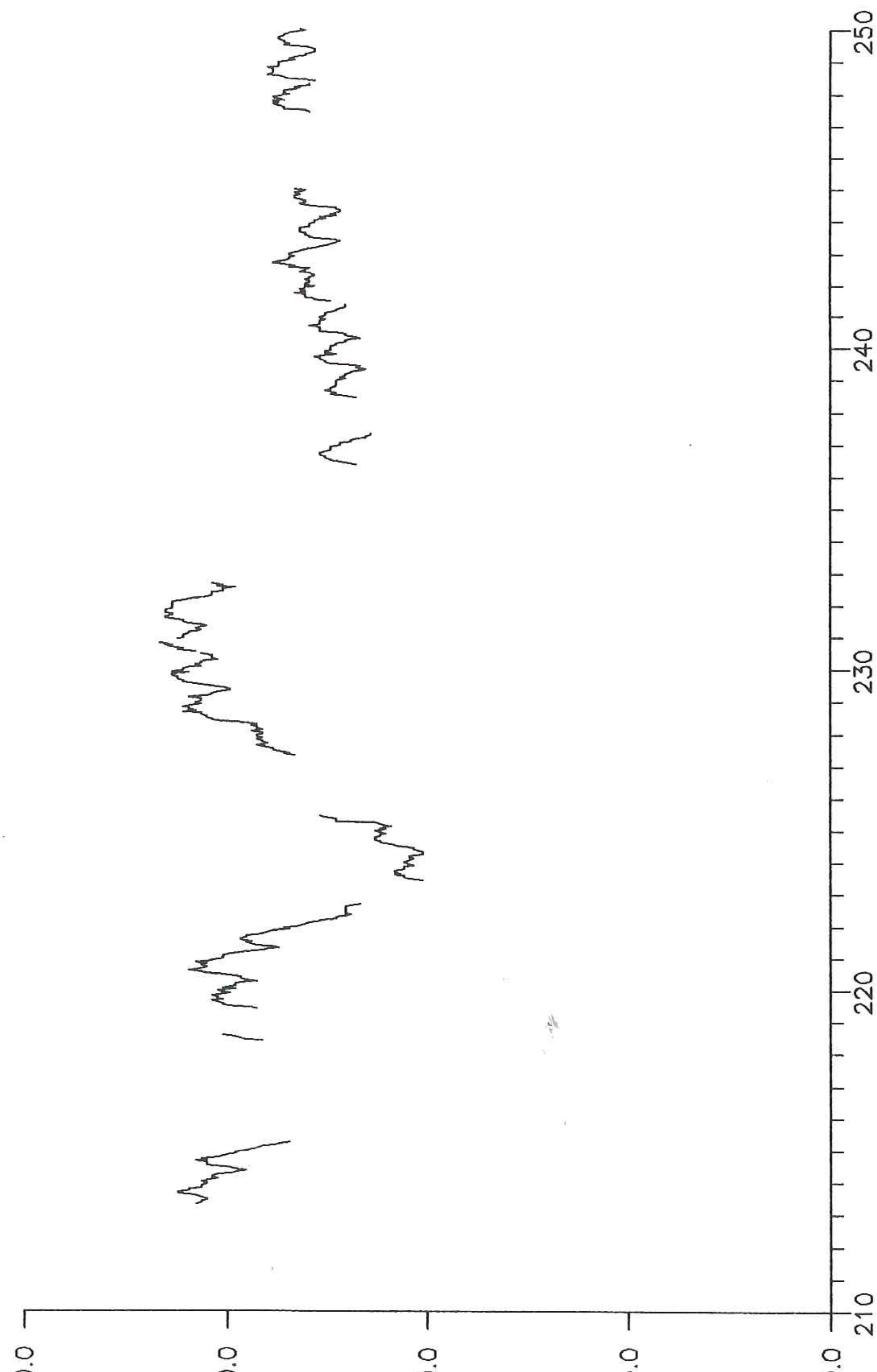


Figure 32 (continued). Discharge (m^3 s^{-1}) from Batura Glacier in the ablation season of 1991.

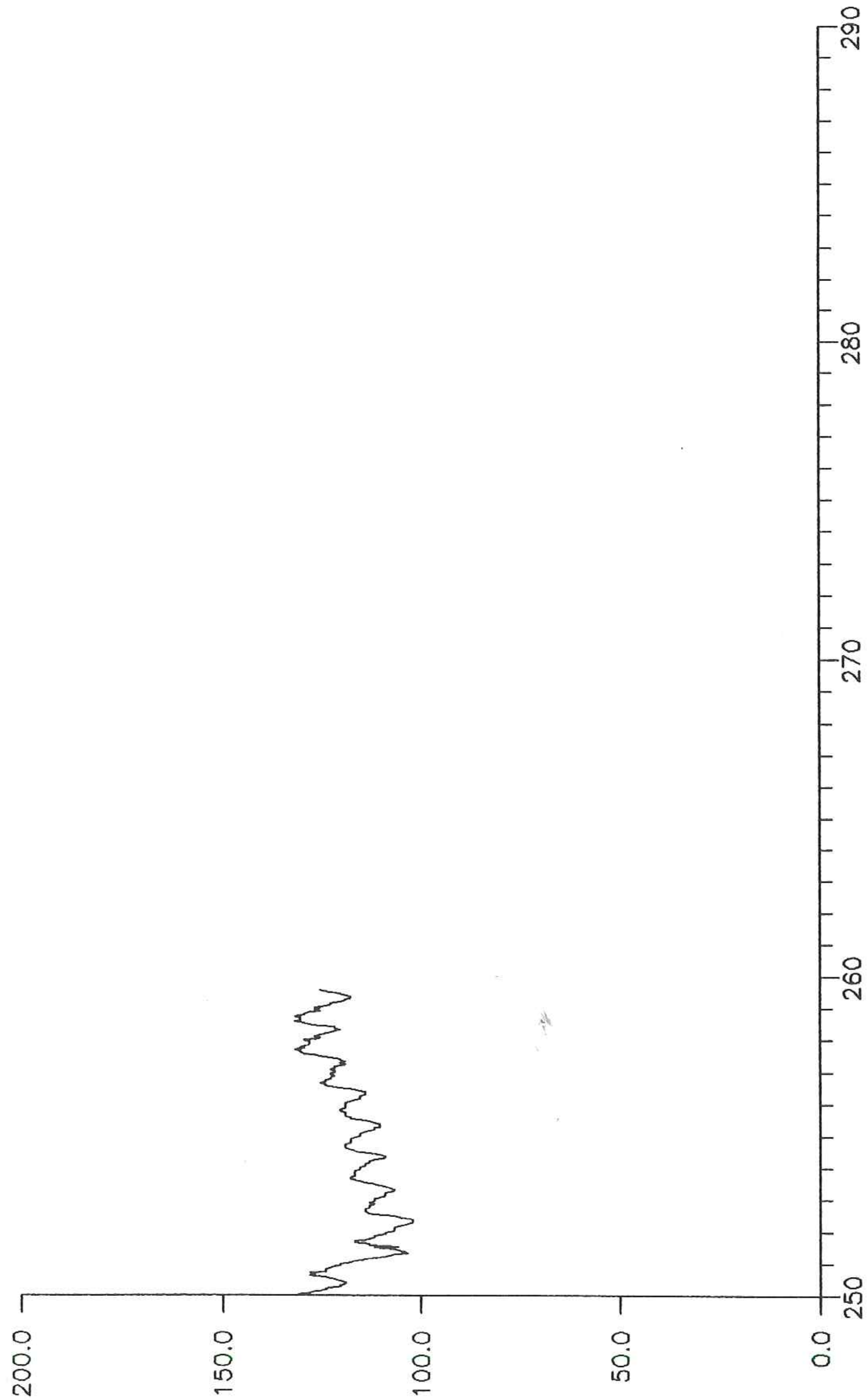


Figure 32 (continued). Discharge (m^3 s^{-1}) from Batura Glacier in the ablation season of 1991.

Volumetric measurements of runoff from Batura Glacier by Lanzhow Institute (1980) confirm the values obtained by UMAGP.

12. Water quality measurements

12.1 Electrical conductivity

EC was monitored at Passu and Batura Bridges in 1989, from mid-May to early October. The pattern of diurnal variation of EC at Batura was the usual rhythm of inverse roughly-phased relationship with discharge with a steady rise to daily maximum before a sudden fall with the onset of ablation. Gradually, as summer progresses the diurnal range of EC increased again as expected (Figure 33). At Passu, the diurnal range of EC was subdued, and the extending of the range of EC during summer failed to occur (Figure 34). A proglacial lake had developed immediately in front of the retreating glacier terminus, and through which all the meltwater had to pass in flowing to the gauging station.

For a short period at the end of May 1989, an attempt was made to evaluate the effect of the lake on the EC of meltwater draining through the lake. A conductivity meter and probe were installed on a rocky ledge about 2m in front of the glacier snout in the 5m moraine strewn area before the lake. After a few days, a rock slide from the glacier ice cliff terminated the experiment. A comparison of the measured EC at this point where the stream emerged from the glacier portal (Figure 35) with EC measured downstream of the lake at Passu Bridge reveals the extent to which the diurnal rhythmic variation in EC is damped by the passage of the flow through the lake. Water quality measurements were therefore continued only at Batura.

Measurement of EC in 1990 commenced at Batura gauge in April, and characteristics of the early season dissolved solids load were observed. EC fell from low flow high values of 118 uS cm^{-1} to around 50 uS cm^{-1} in May, before stabilising with a mean value of the diurnal variations of about 40 uS cm^{-1} as shown in Figure 36, which continued as in 1989 and 1991 to the end of the ablation season. Electrical conductivity falls rapidly as discharge increases, but actually in the first period of rapid enhancement of flow conductivity levels remain broadly stable, with some recovery. EC then falls steadily as discharge slowly increases during May and June. The next rapid increase in discharge affects EC which falls again lower. The lowest solute content is associated with the highest flows of the year in July or August. Solute content of meltwater is affected by residence time of the water in contact with subglacially-derived sediment. Thus, delay to runoff by storage has

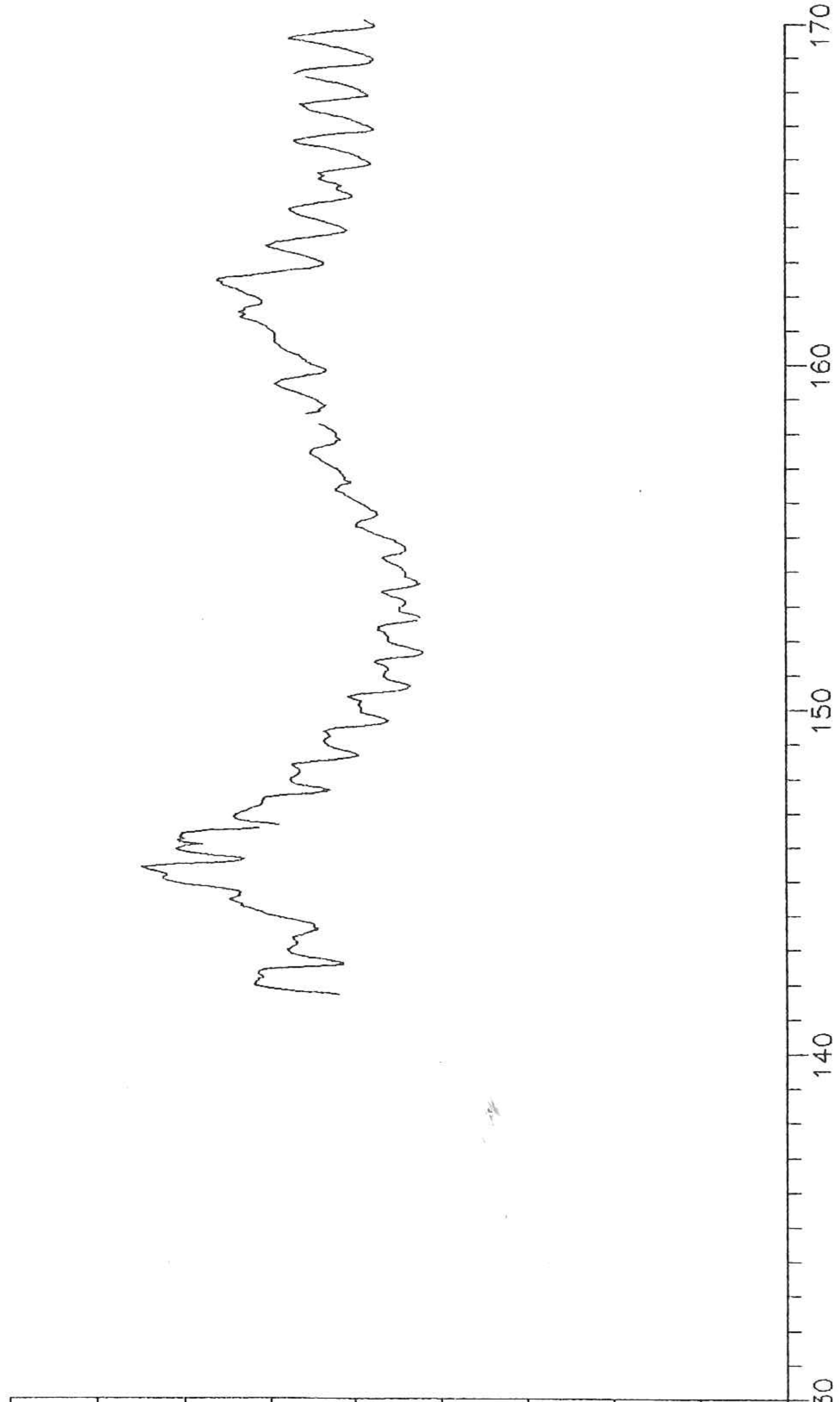


Figure 33. Electrical conductivity (uS cm^{-1}) of meltwater draining from Batura Glacier in the ablation season between 21 May and 7 September 1989

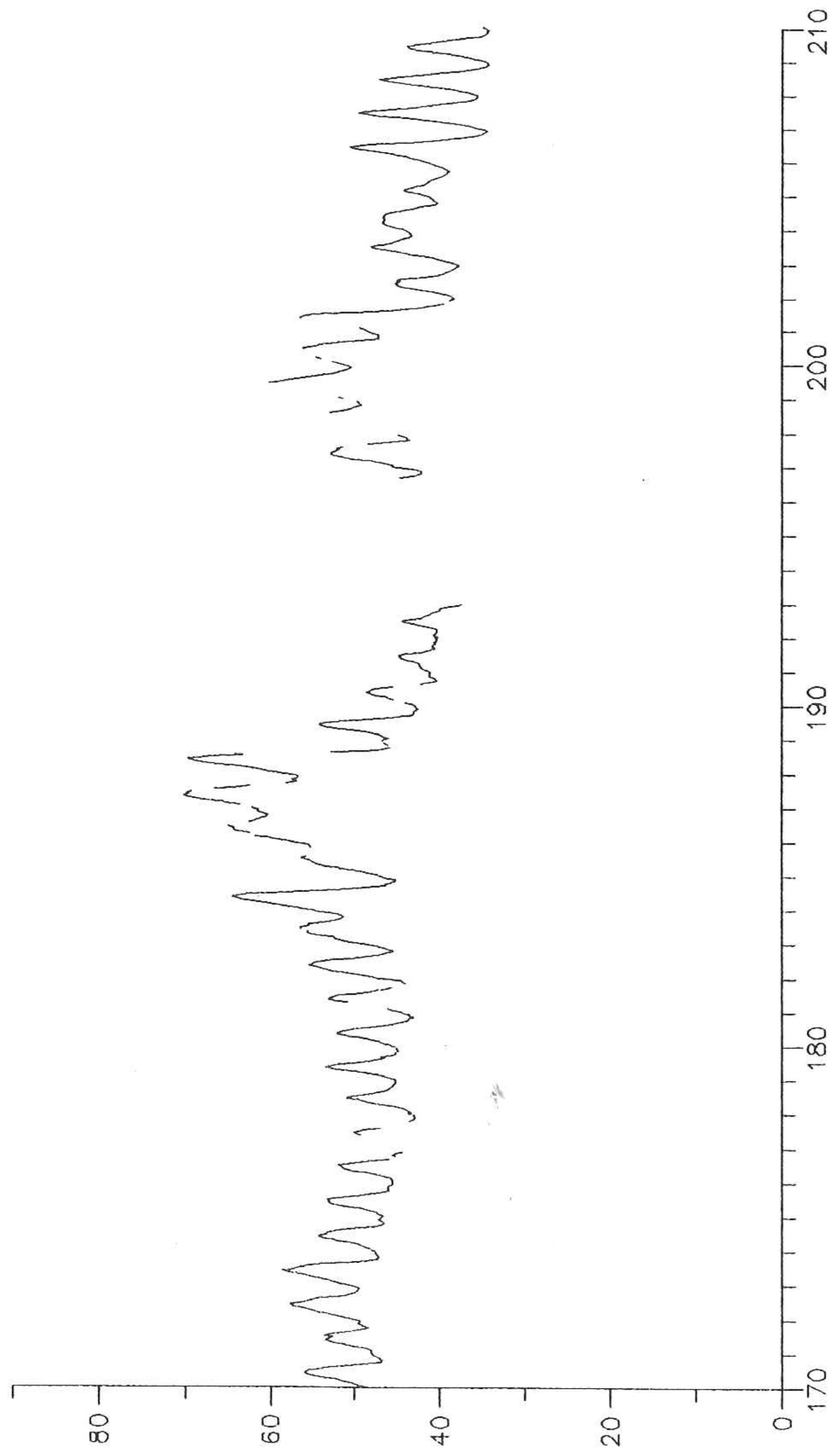


Figure 33 (continued). Electrical conductivity (uS cm^{-1}) of meltwater draining from Batura Glacier in the ablation season between 21 May and 7 September 1989

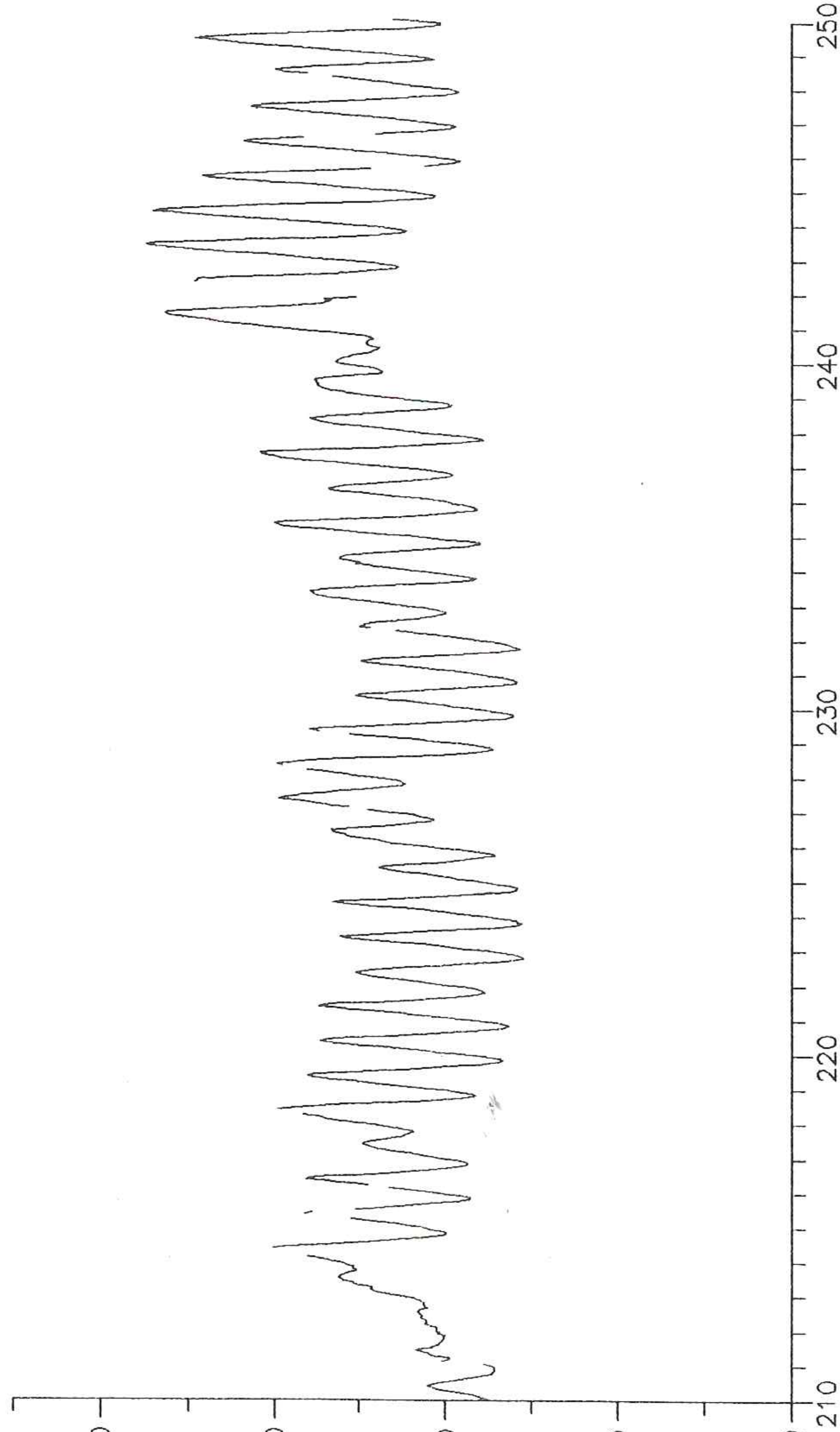


Figure 33 (continued). Electrical conductivity (uS cm^{-1}) of meltwater draining from Batura Glacier in the ablation season between 21 May and 7 September 1989

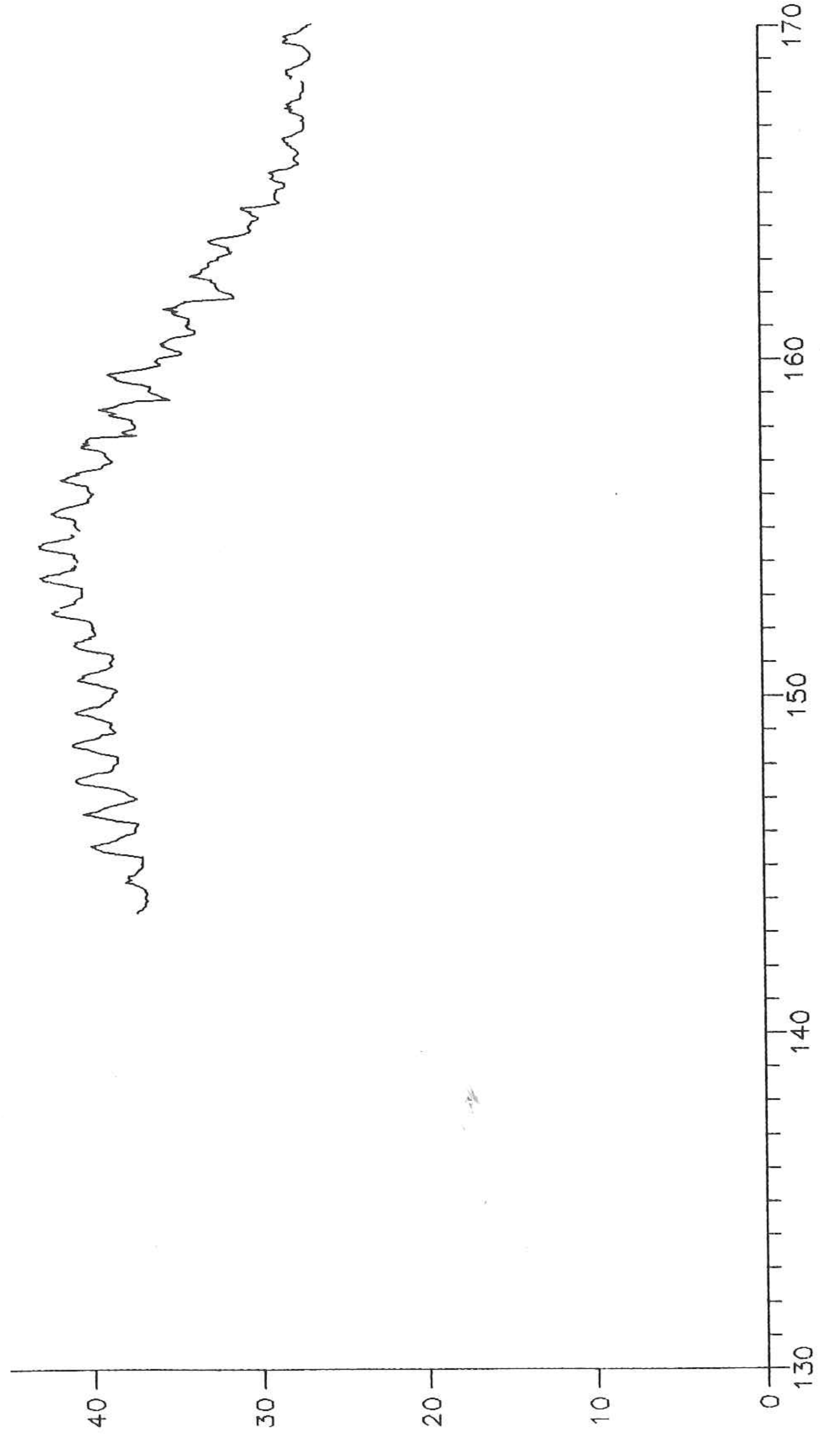


Figure 34. Electrical conductivity (uS cm^{-1}) of meltwater draining from Passu Glacier in the ablation season between 21 May and 5 October 1989

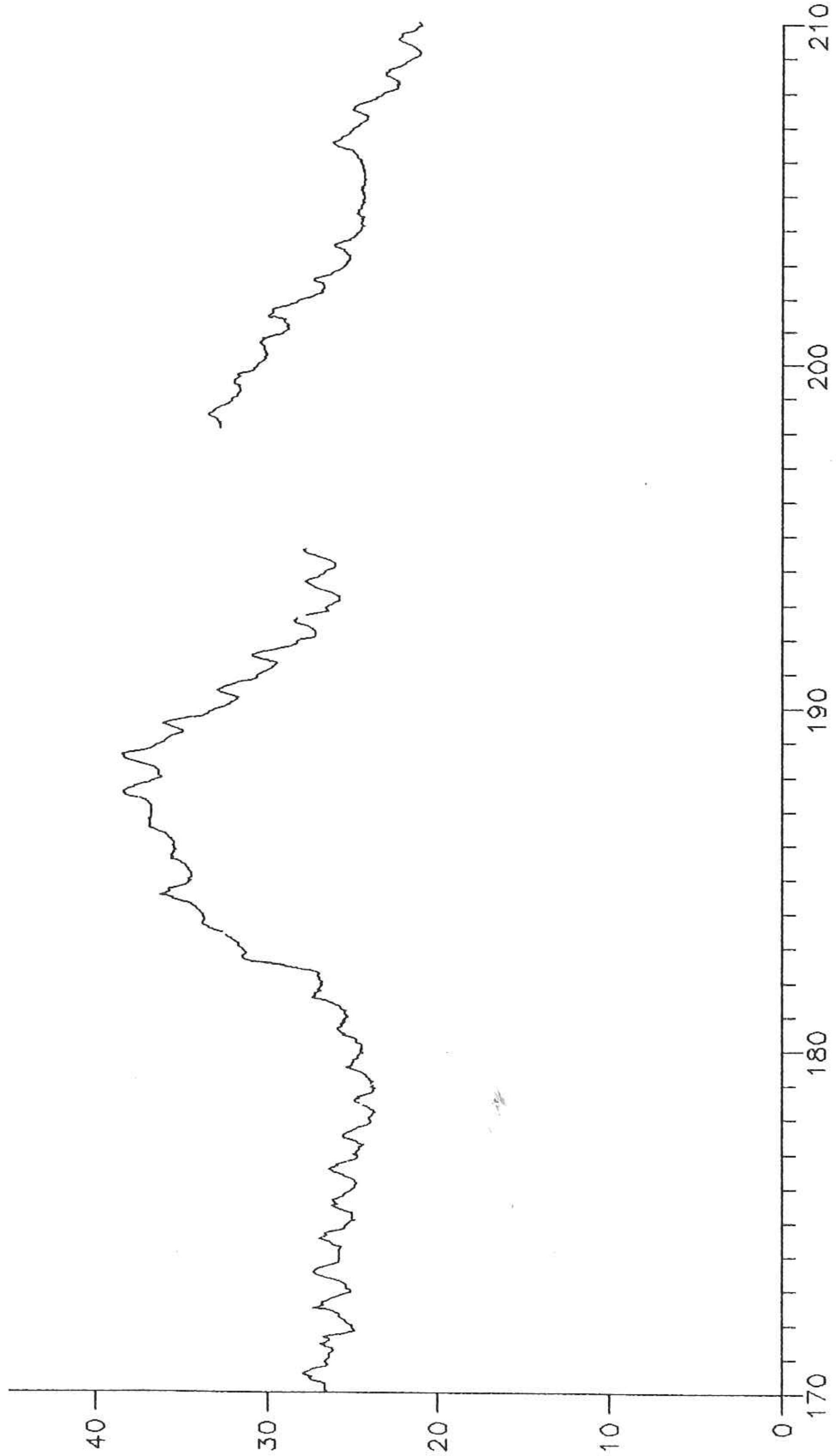


Figure 34 (continued). Electrical conductivity (uS cm^{-1}) of meltwater draining from Passu Glacier in the ablation season between 21 May and 5 October 1989

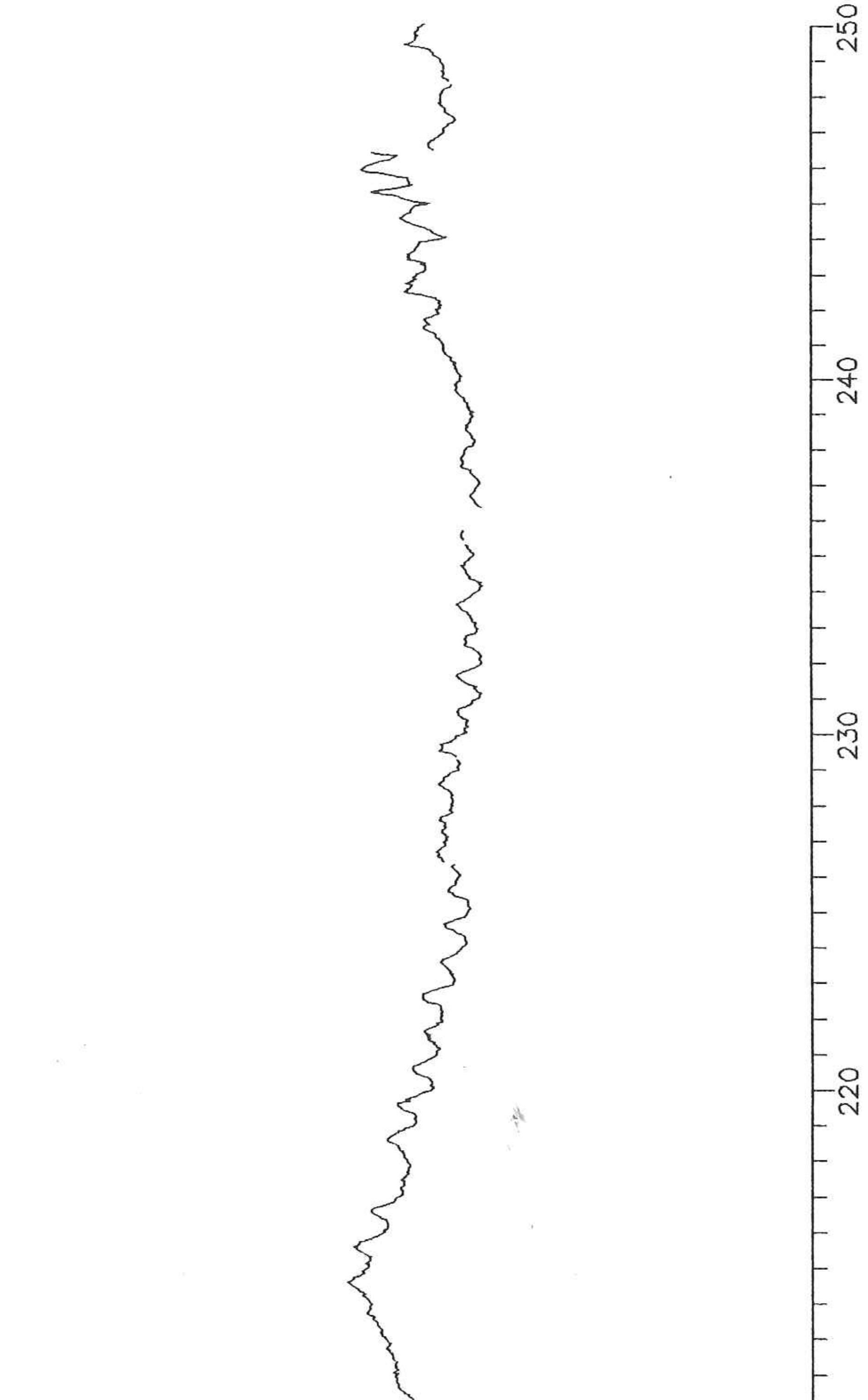


Figure 34 (continued). Electrical conductivity (uS cm^{-1}) of meltwater draining from Passu Glacier in the ablation season between 21 May and 5 October 1989

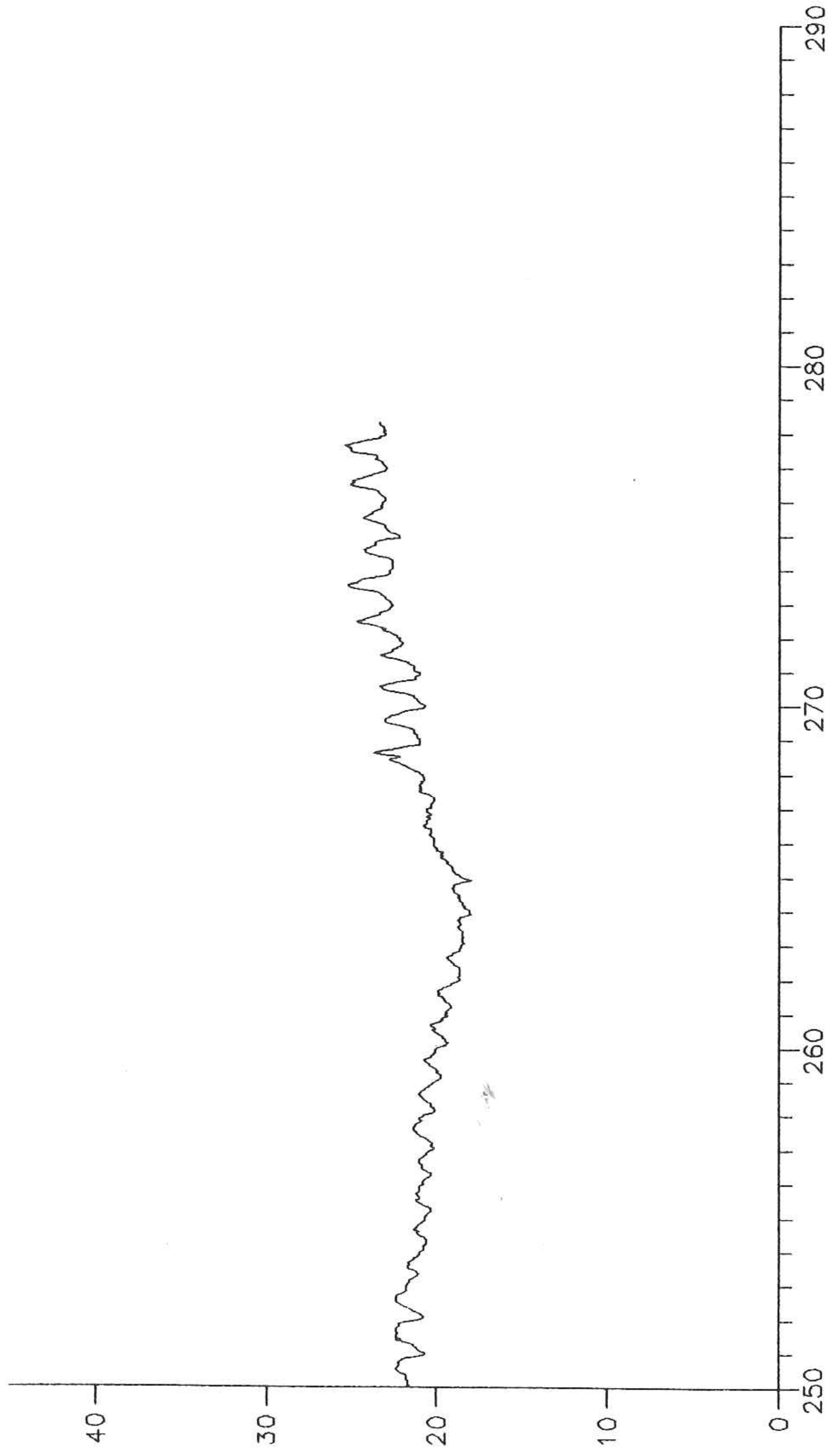


Figure 34 (continued). Electrical conductivity (uS cm^{-1}) of meltwater draining from Passu Glacier in the ablation season between 21 May and 5 October 1989

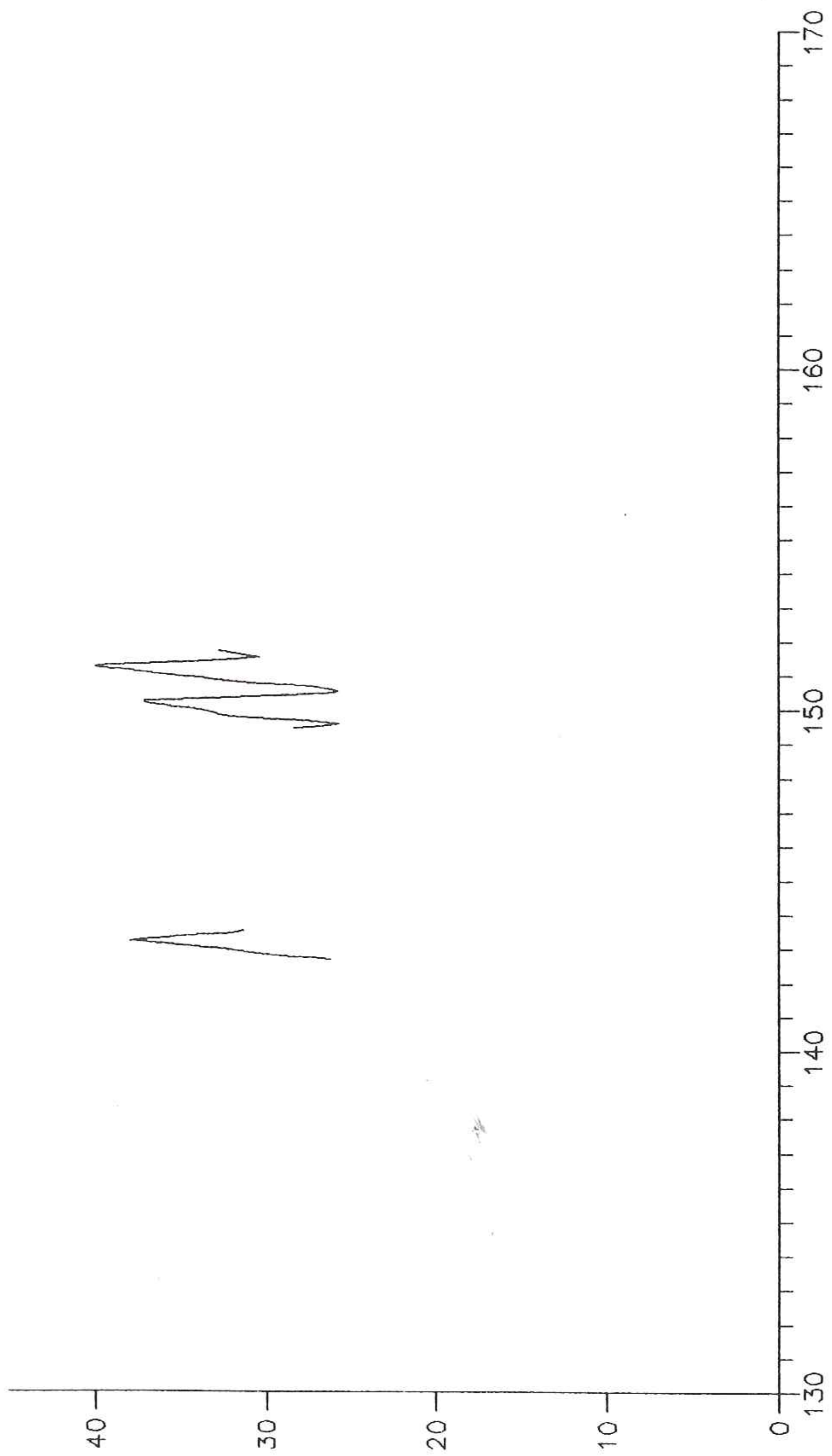


Figure 35. Electrical conductivity (uS cm^{-1}) of meltwater draining from Passu Glacier measured at the actual glacier terminus upstream of the lake in 1989.

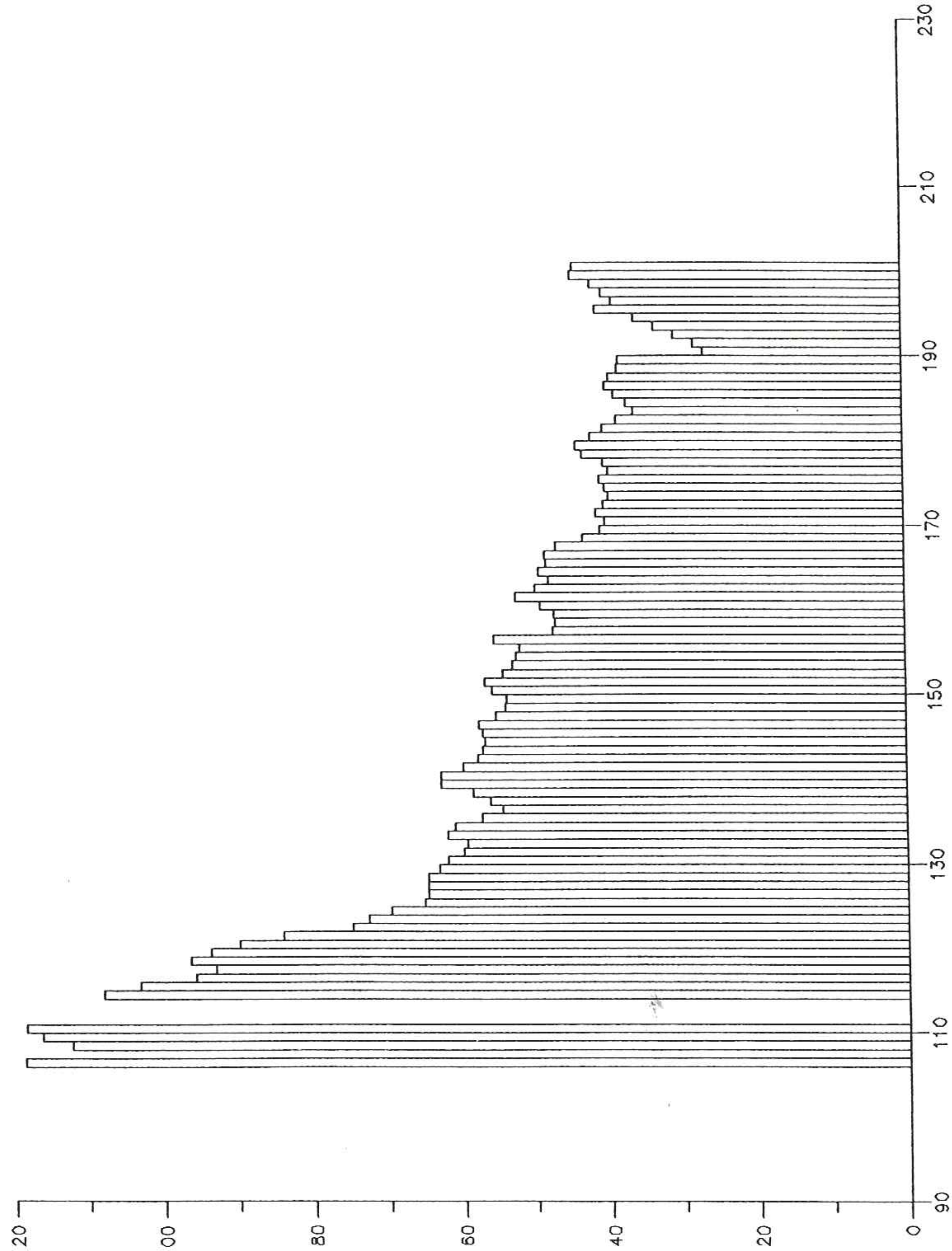


Figure 36. Daily mean electrical conductivity (uS cm^{-1}) of meltwater draining from Batura Glacier in 1990.

been reduced before the first increase in flow in spring.

12.2 Suspended sediment content of meltwater

In order to assess the sediment load of rivers draining from glaciers, suspended sediment content of meltwaters was determined at hourly intervals at Passu and Batura in 1989. At Batura Glacier, with a background level of about 1.0 g L^{-1} with a regular diurnal rhythm, occasional sudden increases in sediment concentration to levels above 3.0 g L^{-1} are interjected (Figure 37). Periods of generally higher sediment content at around 2.0 g L^{-1} accompany increases in the general level of flow. This is the expected pattern of sediment interaction with meltwaters (Collins 1989).

Both the pattern and concentration of sediment transported from Passu Glacier were anomalous. There is no marked diurnal rhythm, few short-lived pulses of higher sediment content, and a generally low level of about 0.5g L^{-1} of sediment (Figure 38). The explanation is that the lake which has developed since 1980 in front of Passu Glacier now traps much of the sediment carried by the meltwater emerging from the portal. There is much less impact on the diurnal variation of discharge of water, however, than on the suspended sediment content and EC. Measurements were therefore discontinued at Passu, but continued in 1990 and 1991 at Batura (see Appendices 2 and 3).

12.3 Suspended sediment load transported in the meltwaters draining from Batura Glacier

Suspended sediment load can be obtained as the product of hourly sampled instantaneous sediment concentration and discharge averaged over the hourly period which the sample represents. Daily total sediment transport is then the sum of all these products after multiplication up to hourly values (i.e. hourly total transport = instantaneous load x 3600 g). Loads of suspended sediment transported from Batura Glacier in 1989 and 1990 are given in Tables 3 and 4 respectively.

Considerably larger quantities of suspended sediment were transported in 1990 than in 1989. The largest quantities of sediment per day were removed from the basin on in the first part of the ablation season, in particular in the early part of July when for the first time for nine months flows reach relatively high summer levels. In 1989, sediment transport infrequently reached 20×10^3 tonnes day^{-1} whereas in 1990, before 13 August, daily total sediment transport remained above 30×10^3 tonnes day^{-1}.

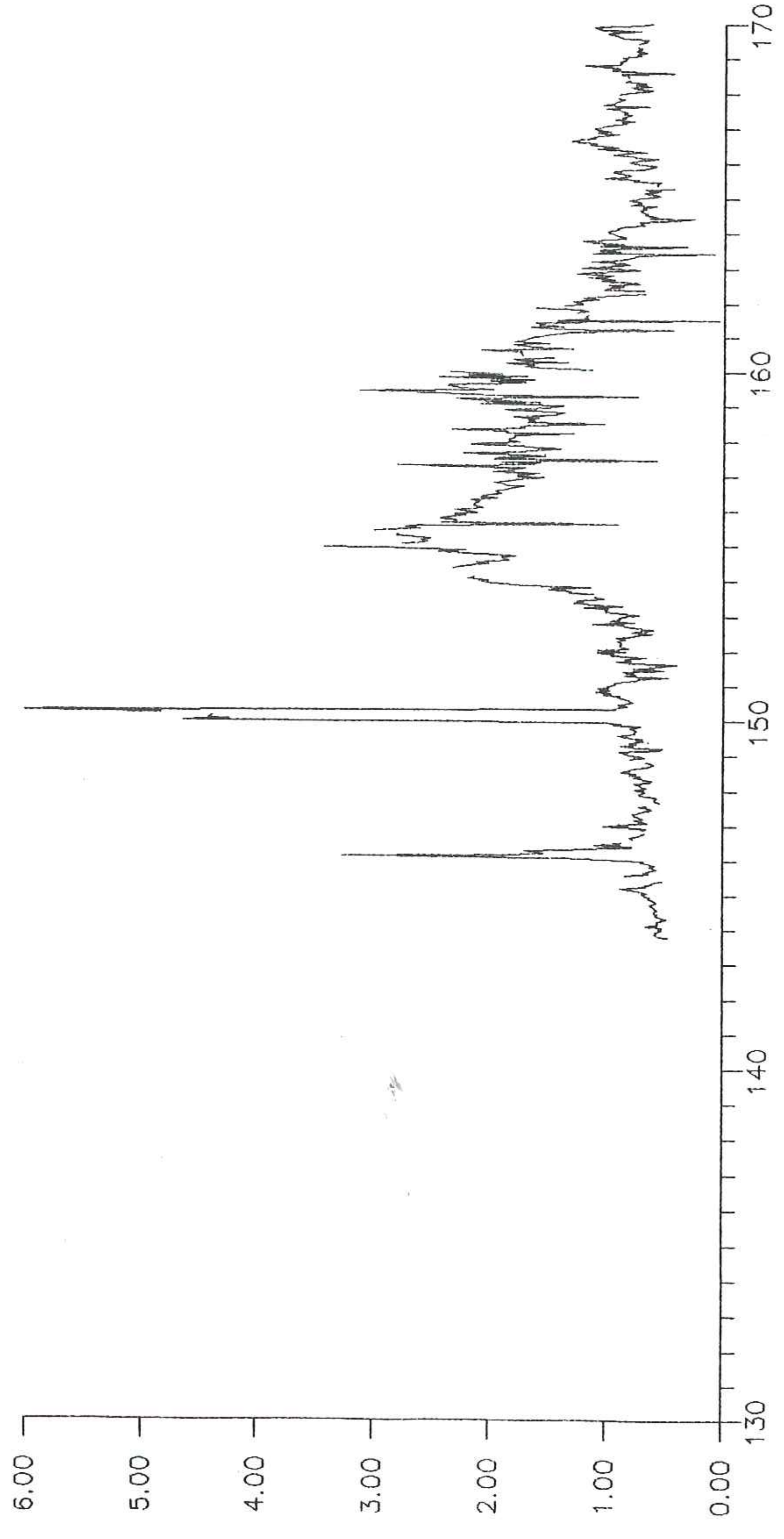


Figure 37. Suspended sediment concentration (g L^{-1}) in meltwaters draining from Batura Glacier in 1989.

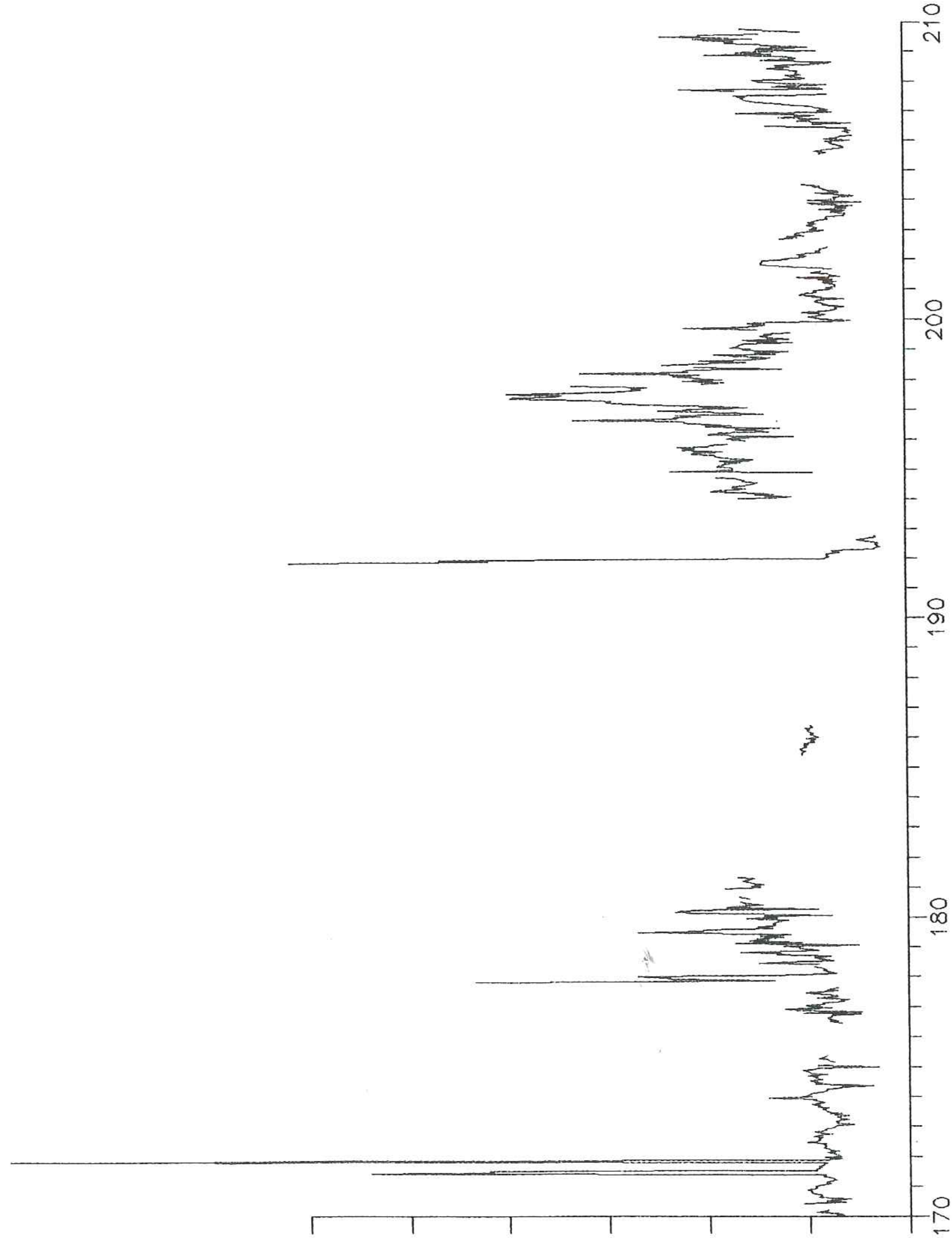


Figure 37 (continued). Suspended sediment concentration (g L^{-1}) in meltwaters draining from Batura Glacier in 1989.

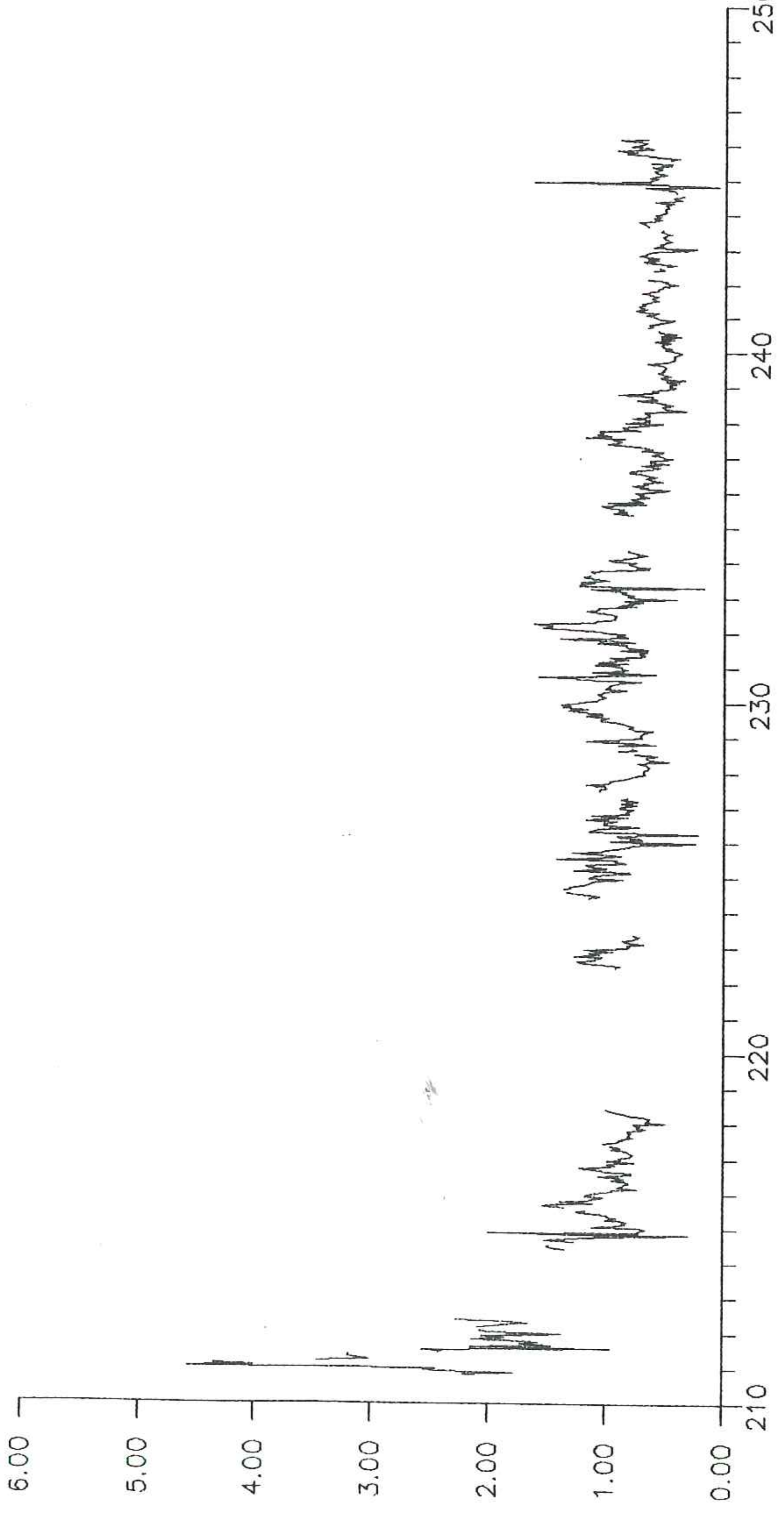


Figure 37 (continued). Suspended sediment concentration (g L^{-1}) in meltwaters draining from Batura Glacier in 1989.

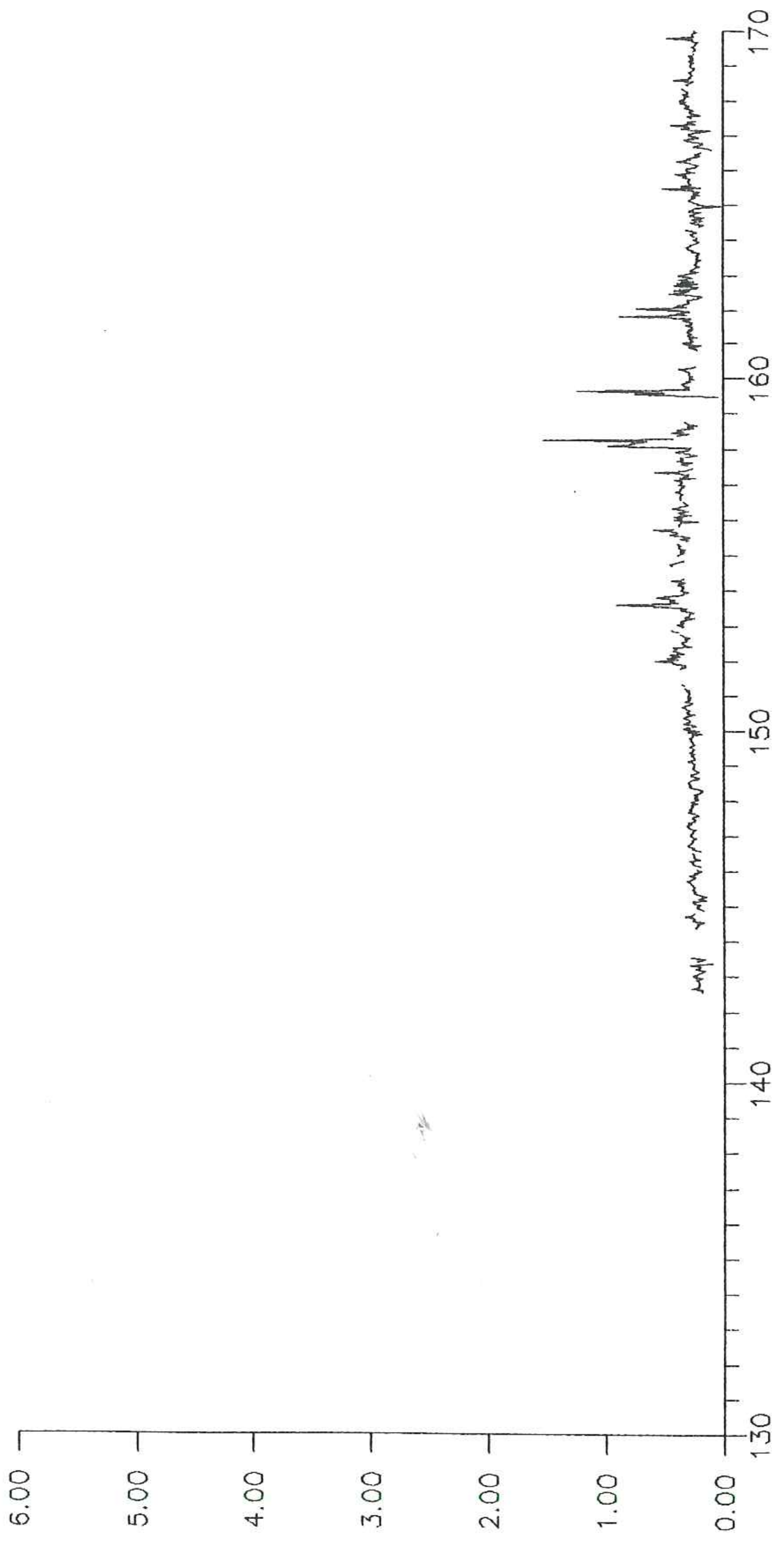


Figure 38. Suspended sediment concentration ($g\ L^{-1}$) in meltwaters draining from Passu Glacier in 1989.

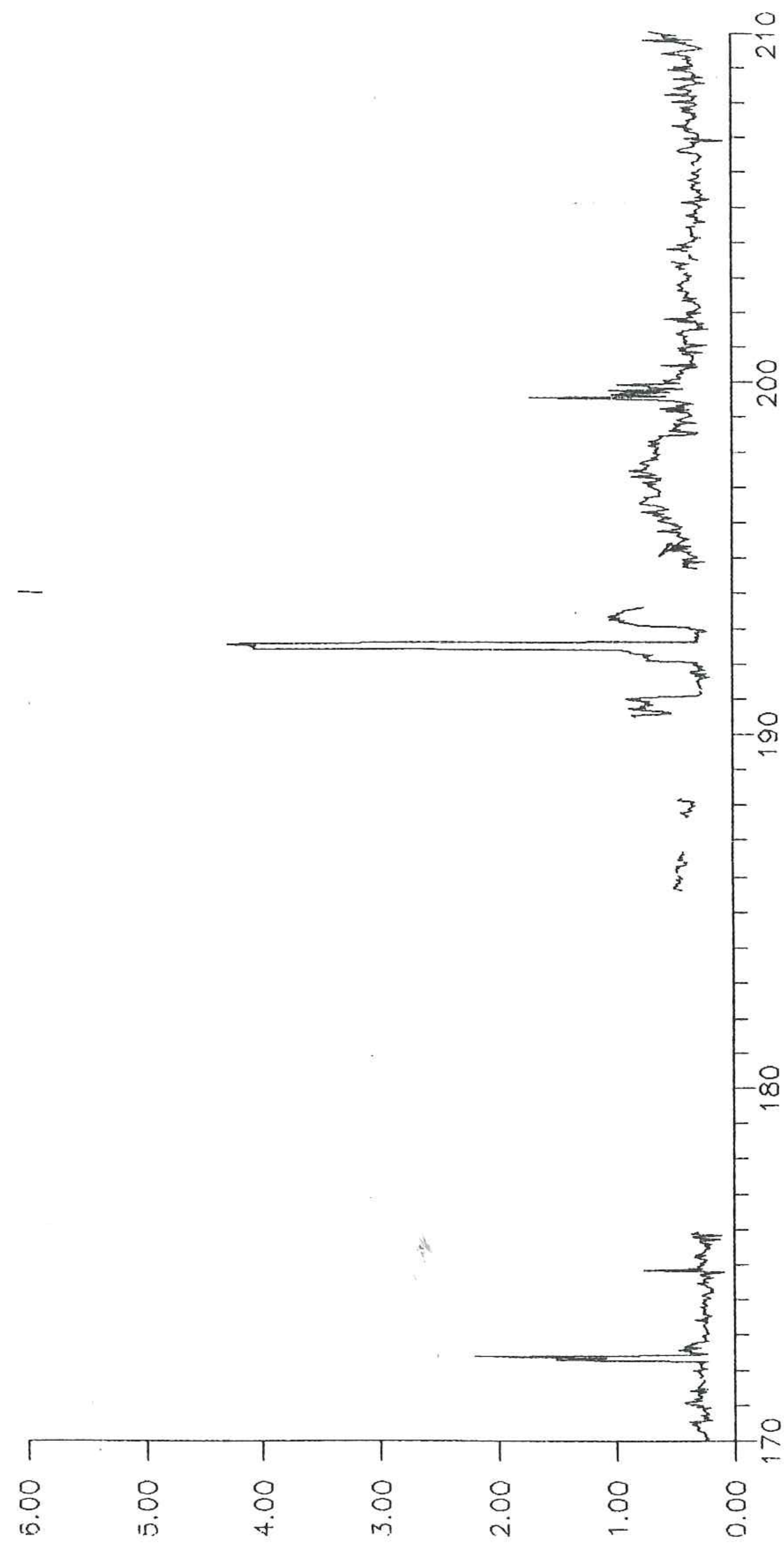


Figure 38 (continued). Suspended sediment concentration ($g\ L^{-1}$) in meltwaters draining from Passu Glacier in 1989.

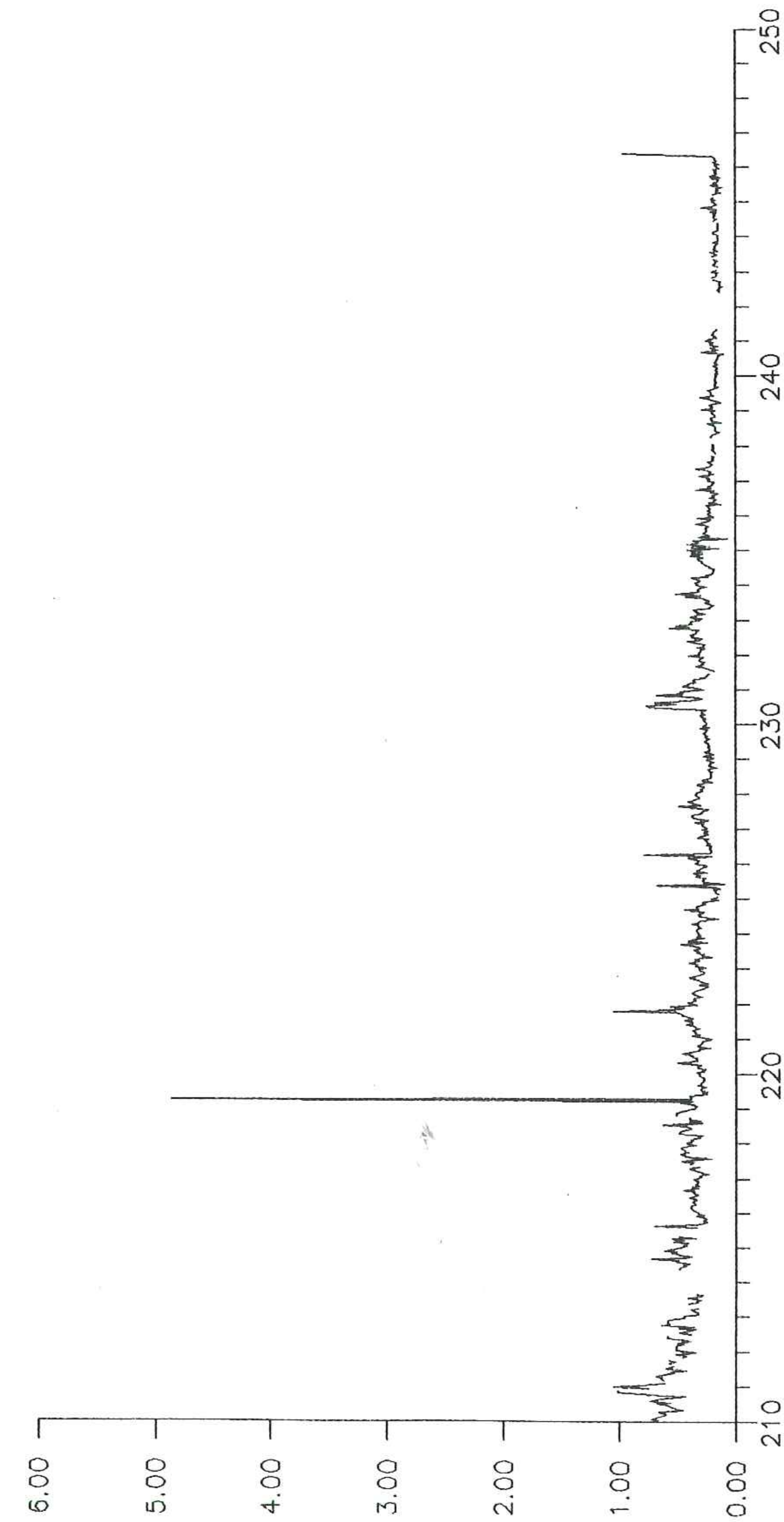


Figure 38 (continued). Suspended sediment concentration (g L^{-1}) in meltwaters draining from Passu Glacier in 1989.

Table 3. Suspended sediment load (tonne day^{-1}) transported by meltwater draining from Batura glacier in 1989.

Day	Date			Load
143	23	5	1989	2948.607
144	24	5	1989	3052.685
145	25	5	1989	3477.991
146	26	5	1989	7072.710
147	27	5	1989	3852.057
148	28	5	1989	4457.443
149	29	5	1989	5139.000
150	30	5	1989	14413.613
151	31	5	1989	5971.575
152	1	6	1989	6998.515
153	2	6	1989	10730.664
154	3	6	1989	21106.258
155	4	6	1989	25765.789
156	5	6	1989	20689.107
157	6	6	1989	19632.043
158	7	6	1989	20867.912
159	8	6	1989	20641.707
160	9	6	1989	18501.742
161	10	6	1989	14847.516
162	11	6	1989	10415.260
163	12	6	1989	9055.793
164	13	6	1989	7158.380
165	14	6	1989	6740.234
166	15	6	1989	9149.296
167	16	6	1989	8488.834
168	17	6	1989	7591.704
169	18	6	1989	7513.344
170	19	6	1989	7634.166
171	20	6	1989	7234.675
172	21	6	1989	999.999
173	22	6	1989	999.999
174	23	6	1989	999.999
175	24	6	1989	999.999
176	25	6	1989	999.999
177	26	6	1989	999.999
178	27	6	1989	999.999
179	28	6	1989	999.999
180	29	6	1989	999.999
181	30	6	1989	999.999
182	1	7	1989	999.999
183	2	7	1989	999.999
184	3	7	1989	999.999
185	4	7	1989	999.999
186	5	7	1989	999.999
187	6	7	1989	999.999
188	7	7	1989	999.999
189	8	7	1989	999.999
190	9	7	1989	999.999
191	10	7	1989	999.999
192	11	7	1989	999.999
193	12	7	1989	999.999
194	13	7	1989	999.999
195	14	7	1989	32668.875

Table 3 (continued) Suspended sediment load (tonne day^{-1}) transported by meltwater draining from Batura glacier in 1989.

Day	Date			Load
196	15	7	1989	29987.008
197	16	7	1989	39186.773
198	17	7	1989	23845.010
199	18	7	1989	16681.131
200	19	7	1989	9605.868
201	20	7	1989	10807.332
202	21	7	1989	11701.579
203	22	7	1989	9436.456
204	23	7	1989	9290.625
205	24	7	1989	9791.509
206	25	7	1989	10960.899
207	26	7	1989	17273.027
208	27	7	1989	17242.645
209	28	7	1989	23671.832
210	29	7	1989	36167.773
211	30	7	1989	40516.484
212	31	7	1989	30200.438
213	1	8	1989	999.999
214	2	8	1989	15212.357
215	3	8	1989	10286.680
216	4	8	1989	999.999
217	5	8	1989	999.999
218	6	8	1989	999.999
219	7	8	1989	999.999
220	8	8	1989	999.999
221	9	8	1989	999.999
222	10	8	1989	999.999
223	11	8	1989	999.999
224	12	8	1989	999.999
225	13	8	1989	999.999
226	14	8	1989	999.999
227	15	8	1989	999.999
228	16	8	1989	999.999
229	17	8	1989	999.999
230	18	8	1989	999.999
231	19	8	1989	999.999
232	20	8	1989	999.999
233	21	8	1989	999.999
234	22	8	1989	999.999
235	23	8	1989	999.999
236	24	8	1989	999.999
237	25	8	1989	999.999
238	26	8	1989	999.999
239	27	8	1989	999.999
240	28	8	1989	999.999
241	29	8	1989	999.999
242	30	8	1989	999.999
243	31	8	1989	999.999
244	1	9	1989	999.999
245	2	9	1989	5610.859
246	3	9	1989	5256.852
247	4	9	1989	999.999
248	5	9	1989	999.999

999.999 No measurement

Table 4. Suspended sediment load (tonne day^{-1}) transported by meltwater draining from Batura glacier in 1990.

Day	Date			Load
178	27	6	1990	41200.422
179	28	6	1990	39917.383
180	29	6	1990	37125.125
181	30	6	1990	46845.695
182	1	7	1990	40835.031
183	2	7	1990	33227.051
184	3	7	1990	39928.574
185	4	7	1990	55874.602
186	5	7	1990	70686.125
187	6	7	1990	51562.164
188	7	7	1990	57794.496
189	8	7	1990	66568.875
190	9	7	1990	70478.234
191	10	7	1990	59440.500
192	11	7	1990	48382.121
193	12	7	1990	36314.266
194	13	7	1990	32825.449
195	14	7	1990	35630.473
196	15	7	1990	40562.883
197	16	7	1990	39026.145
198	17	7	1990	36989.277
199	18	7	1990	34621.000
200	19	7	1990	33678.465
201	20	7	1990	33153.016
202	21	7	1990	28227.051
203	22	7	1990	20738.246
204	23	7	1990	22443.326
205	24	7	1990	26950.258
206	25	7	1990	31402.555
207	26	7	1990	35141.281
208	27	7	1990	32594.391
209	28	7	1990	50666.266
210	29	7	1990	50233.039
211	30	7	1990	46763.051
212	31	7	1990	48242.355
213	1	8	1990	49799.633
214	2	8	1990	51157.961
215	3	8	1990	58606.211
216	4	8	1990	52799.539
217	5	8	1990	43393.508
218	6	8	1990	46072.051
219	7	8	1990	50848.516
220	8	8	1990	47683.148
221	9	8	1990	51424.602
222	10	8	1990	72099.031
223	11	8	1990	58734.539
224	12	8	1990	999.999
225	13	8	1990	41771.996
226	14	8	1990	32752.578
227	15	8	1990	16440.455
228	16	8	1990	14553.313
229	17	8	1990	14242.645
230	18	8	1990	17556.406

Table 4 (continued) Suspended sediment load (tonne day^{-1}) transported by meltwater draining from Batura glacier in 1990.

Day	Date			Load
231	19	8	1990	20708.578
232	20	8	1990	22648.436
233	21	8	1990	22818.023
234	22	8	1990	21478.945
235	23	8	1990	999.999
236	24	8	1990	15900.932
237	25	8	1990	13961.182
238	26	8	1990	12269.954
239	27	8	1990	16650.801
240	28	8	1990	16425.004
241	29	8	1990	999.999
242	30	8	1990	18931.086
243	31	8	1990	15472.762
244	1	9	1990	11472.422
245	2	9	1990	999.999
246	3	9	1990	999.999
247	4	9	1990	999.999
248	5	9	1990	999.999
249	6	9	1990	999.999
250	7	9	1990	999.999
251	8	9	1990	999.999
252	9	9	1990	999.999
253	10	9	1990	999.999
254	11	9	1990	999.999
255	12	9	1990	999.999
256	13	9	1990	999.999
257	14	9	1990	999.999
258	15	9	1990	999.999
259	16	9	1990	999.999
260	17	9	1990	999.999
261	18	9	1990	999.999
262	19	9	1990	999.999
263	20	9	1990	10916.594
264	21	9	1990	11473.600
265	22	9	1990	12243.479
266	23	9	1990	12553.305
267	24	9	1990	11897.138
268	25	9	1990	8210.261
269	26	9	1990	8327.224
270	27	9	1990	5545.980
271	28	9	1990	5168.286
272	29	9	1990	5206.389
273	30	9	1990	4810.784
274	1	10	1990	3873.585
275	2	10	1990	3685.914
276	3	10	1990	3310.164
277	4	10	1990	3037.061
278	5	10	1990	3016.841
279	6	10	1990	2421.194
280	7	10	1990	1835.276

999.999 No measurement

13. Evaluation of WAPDA stage reading system

The extent to which reading stage boards 9 times a day on the hour every hour from 08.00 to 16.00 provides a reasonable estimate of the true daily discharge is of relevance for glacier-fed rivers on account of the daily variation of flow. The timing of daily maxima and minima of flow in relation to the hours monitored will determine which fraction of the falling or rising limb of the hydrograph is sampled. Since the rating curve for the critical station at Dainyore Bridge was not available, a test was carried out for the Batura meltstream.

Nine values of discharge were taken at the WAPDA standard times, and the mean of the nine values taken as the estimated daily mean discharge. The actual mean daily discharge from 24 readings on the hour was also calculated. The results for 7 days are given in Table 5. The error of estimation of the daily mean using the 9 hour sampling scheme ranged from -2.80% to +4.02%, with an average error of -0.92%. The stage reading system appears to be providing an estimate very close to the value that would be obtained with continuous monitoring.

14. Conclusions and recommendations

Although stage reading 9 times a day is adequate to characterise daily total flow from a glacierised basin, continuous recording is preferred when flow forecasting and understanding of glacio-hydrological processes are concerned.

The difficulty of acquiring continuous records in rivers of the dimensions of those draining large Karakoram glacierised basins cannot be overestimated. The absolute quantities of summer discharge, the seasonal range of flow, occasional sudden high magnitude outburst events, and the instability of the channels themselves makes the construction of flumes inappropriate and even the maintenance of stable stage boards problematical. The solution for stage boards must be to bring in steel rail or support joist, which might be inserted at a low angle from the boulders of the banks transverse to the direction of flow into the deeper parts of the bed, and fixed there with cement in winter.

Standing waves, turbulence, high velocity and bed load transport, together with shifting channels, aggradation and siltation of the bed profile will have made the measurements of discharge by the

Table 5. Estimates of daily mean discharge at Batura glacier in 1990 from 9 hourly-interval samples between 08.00 and 16.00h.

Date	Timing of minimum	Timing of maximum	$10^6 m^3$ 08-16 sample mean	$10^6 m^3$ actual mean	% deviation
8/4/90	13	23	1.147	1.18	-2.80
8/5/90	7	15	4.941	4.75	+4.02
8/6/90	7	18	53.209	54.33	-2.06
8/7/90	9	18	192.540	195.49	-1.50
8/8/90	8	16	195.321	197.12	-0.91
8/9/90	8	17	82.61	82.96	-0.42
7/10/90	9	16	41.85	42.50	-1.53

velocity-area method less accurate than might normally have been achievecd. Rapid fluctuation of discharge during a gauge compounds the unreliability. Undoubtedly heavier weights are necessary, and while the concept of the Landrover mounted system is excellent, the construction needs to be more robust, both to take the heavier weights, and to ensure mechanical power for raising and lowering the current meter from the water. Fewer verticals in the cross section during a gauge will probably not significantly reduce the accuracy of the measurement of discharge.

Batura and Passu glacier basins are both attractive as representative glacierised basins for the Karakoram mountains, both per se as basins in which to investigate climate-glacier-runoff relations and as basins to represent the glacier contribution to the larger basins such as the Hunza to Dainyore or the upper Indus to Besham. Passu might be preferred on the grounds of size and accessibility and ease of gauging, although prone to glacier outburst floods. There is a case for having both as experimental basins. There would always be a second set of discharge data being collected in case of disaster at one of the sites. Given that it will be necessary to have on site personnel to rebuild or modify site configurations and to check frequently equipment for malfunction and replace or repair, and to undertake sediment measurements, there would be little additional cost in running a second station.

From a flow forecasting viewpoint, air temperature measurements at high altitude provide the best relationship with discharge. Degree days clearly have predictive power, but it is clear that measurements are necessary at several elevations. Lapse rates are variable, and the marginal addition of area to increase the area of ice exposed to ablation with the ascent of the transient snow line ensures that stations towards or at the equilibrium line are essential later in the ablation saeson. Whatever model is selected for prediction, measurement of energy input variables such as air temperature and global radiation will be necessary at elevations close to the equilibrium line.

Suspended sediment delivery from Karakoram glacierised basins will be exceptionally high if the loads transported by meltwaters from Batura Glacier are typical. Water quality variables provide some information also about subglacial processes and the record from Batura is valuable also in that respect. To that end, the basin of Batura Glacier would be preferred to that of Passu Glacier in which water quality signals are damped by the presence of the lake revealed or permitted to form by glacier recession. Continuing retreat however will allow water quality variables, and stage, to be measured upstream of the lake, in which case, in a few years Passu would take over as the flagship site. The gauging station would of course have to remain at the Karakoram Highway bridge.

Considerable experience has been gained by both UMAGP and WAPDA in operating at high elevation in the hostile Karakoram environment. This experience has allowed the collection of data for four ablation seasons, of which three long continuous parallel energy and runoff series can form the basis of modelling, and all of which are useful with respect to estimating basin water resource availability.

Measurements should continue at both Passu and Batura. In the years 1989 through 1992, considerable year-to-year variation in the quantity of runoff has been indicated. Impending climatic warming may affect runoff in a variety of ways; positively through increased sensible heat for melting and arguably negatively through reduction of receipt of radiation by cloud cover and enhanced snowfall, should warmer air also be moister. Both would delay the rise of the transient snow line in spring and summer.

Instrumentation of one or two flagship basins for a longer term monitoring of climatic influences on meltwater production should not only build on the experience now gained in SIHP by UMAGP and WAPDA but also include measurement of ablation of ice against stakes on the glacier surfaces so that actual melt can be implicitly included in models. Data records will be improved with a more permanent high elevation meteorological installation at Patundas, floating pontoons as platforms for water quality sensors at the gauging stations, and ultrasonic water level recorders in preference to submerged pressure transmitters.

Finally, a model must be chosen for prediction. Whilst a simple degree day model may suffice with suitable high level meteorological measurements, a model in which the transient snow-line is allowed to rise will be more physically-based, be transferable to other basins and ultimately be more reliable for forecasting. ODA may wish to consider a development with WAPDA in that direction.

Acknowledgements

The author wishes to acknowledge the assistance of the many people in the U.K. and Pakistan who enabled the success of this project. In particular: the following from UMAGP in the Karakoram: S. Anderton, G. A. J. Boyce, R. A. Boyce, C. Bradley, D. A. Byrne, H. Capel Cure, P. Cutler, S. Devereux, E. Gill, R. Hawley, P. Hodgson, J. D. Keeley, R. E. J. Kelly, A. Jarvis, C. Jarvis, P. Jordan, R. Loughborough, A. Lowe, R. McGowan, P. Mustow, T. Muten, J. R. Rubery; from UMAGP in Manchester, A. Barrett and G. Williams; from the ODA: P. Barfoot, D. Fidler in London, C. Hunt, R. Leverington and R. Marshall in

Islamabad; from WAPDA: Tariq Massoul, Hasnain Shah, Mohammed Younas; and in Passu, I. Baig, P. Baig. The Royal Society provided additional funding in 1991 and 1992. The University of Manchester through the Deopartment of Geography, the H. E. David Travel Scholarship Funds, and the Zochonis Fund enabled the participation of the many undergraduates, without whose participation and suffering, the repetitive trivial tasks necessary to support a data collection exercise of this scale would not have been done.

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